ALTERNATING CURRENT DESIGN

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ALTERNATING CURRENT DESIGN

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PREFACE

Let me say at once that this book does not, and is not meant to, cover the whole of the subject suggested by its title. It is intended, for instance, to be a companion book to Mr. Cramp's "Continuous Current Machine Design," to which treatise the reader is referred for much of the ground that would otherwise have been twice traversed, as, for example, the sections on Temperature Rise and Insulation, together with nearly all the purely mechanical parts of design, including works costing.

Of the rest, I have perhaps aimed at giving that which I have not found in similar books, and particularly have I aimed at expressing it in a non-mathematical way, endeavouring to emphasize the inward physical meaning rather than the outward mathematical form, to impart ideas rather than information.

I hope the book will be useful alike to students and to those engaged in works, and I sometimes dare to hope that my brother designers will find one or two things presented in a new light which may stimulate them even whilst disagreeing.

Of those to whom I have become indebted over the compilation of this book I shall have space only to mention a few. My friend and late assistant,

308821

Mr. R. E. Grime, comes easily first, for from his notes I have largely helped myself for material for many of the chapters.

The idea of the price curves for cables is taken from a paper by Mr. H. A. Earle, and the idea of sodium as a conductor from Betts. The costs of most of the more usual metals in Chapter XI. were obtained for me by Messrs. Carrick & Brockbank of this city, and those of the rarer metals by Messrs. Johnson Matthey of London.

I shall at any time be pleased to receive, and if possible to answer, letters of suggestion, criticism or correction.

JULIUS FRITH.

The Homestead,
Victoria Park, Manchester,
November, 1911.

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LIST OF SYMBOLS AND CONTRACTIONS USED

Ap	Area of cable for a loss of p per cent. per mile, in Chapter XI.
AΔ	Area of cable for a density of Δ amperes per in^2. in Chapter XI.
A.T.'s	Ampere turns.
a	Angle between a coil when first observed and its position of maximum flux, in Chapter I.
B	Magnetic induction in lines per cm^2.
C	R.M.S. current in amperes.
Co	Current at no load, hence magnetizing current in Induction Motors, in Chapter VII., etc.
° C.	Degrees Centigrade.
C.G.S.	Centimetre-gramme-second units.
C.S.	Cast steel.
Cu	Copper.
cm.	Centimetre.
cm^2., cm^3.	Square and cubic centimetre.
D	Diameter of stator at the air space, in Chapter III., etc.
d	Diameter of iron core of a transformer, in Chapter IX.
D.C.	Direct current.
Δ	Amperes per square inch in copper.
δ	Radial clearance between stator and rotor of Induction Motor, in Chapter VIII.
	Also density of a metal in grammes per cm^3., in Chapter XI.
E	Maximum value of E.M.F., in Chapter I.
	Elsewhere R.M.S. value of E.M.F.
e_r	Volts lost in resistance of transformer windings, in Chapter IX.

e_s Volts lost in reactance of transformer windings, in Chapter IX.

E.M.F. Electro-motive force in volts.

F. Capacity in farads, in Chapter I.

ϕ Angle between the maximum value of current and volts. $\cos \phi =$ power factor.

H Magnetic lines of force per cm^2. in air, in Chapter I.

Elsewhere C.G.S. magnetizing force per cm.

H.P. Horse-power.

H.T. High tension, in Chapter X.

I Maximum value of alternating current in amperes, in Chapter I.

in. Inches.

in^2., in^3. Square and cubic inch.

K Cost of material in £'s per ton, in Chapter XI.

KW.'s Kilowatts

K.V.A.'s Kilo-volt-amperes.

L Self-induction in henries, in Chapter I.

l Length of an active conductor, gross length of stator plates, axial length of stator.

Also a length in cms. of a magnetic path.

Also the length of a limb of a transformer in Chapter IX.

L.T. Low tension, in Chapter X.

M.S. Mild steel.

mb Function of increase of resistance due to a conductor's own field, in Chapter IV.

mm.'s Milimetres.

N Magnetic flux linking a coil, or per pole, in Chapter I., etc.

Number of slots per pole in "σ" formula, in Chapter VII., etc.

P Phosphorus, in Chapter XI.

Also number of poles.

P.c. Price of copper per in^3., in Chapter IX.

P.i. Price of iron per in^3., in Chapter IX.

p Percentage loss per mile in cables, in Chapter XI.

p.f. Power factor.

Q Maximum quantity of electricity in condenser, in Chapter I.

R Resistance in ohms.

R, r.p.m. Revolutions per minute.

R.M.S. Square root of mean square of a sine wave, Virtual value of an alternating current or voltage.

r length of radial arms of an active conductor, in Chapter I.

ρ Ratio of primary and secondary turns on a transformer, in Chapter IX.

Also specific resistance in microhms per cm^3. at 15° C., in Chapter XI.

S Tensile strength in tons per in^2., in Chapter XI.

Sn Tin.

Si Silicon.

σ $1 + \sigma$ is the waste field coefficient of an Induction Motor, in Chapter VII., etc.

T Turns per phase.

T_1 & T_2 Primary and secondary turns on a transformer, in Chapter IX.

t Time in seconds since the beginning, in Chapter I.

Also depth of copper in transformer coils, in Chapter IX.

θ Angle between the coil and its position of maximum flux, in Chapter I.

τ Pitch of poles, N. to S., in Chapter VII.

V Velocity in cms. per second, in Chapter I.

W Watts output, in Chapter IX.

W.I. Wrought iron.

w.f.c. Waste field coefficient.

Zn Zinc, in Chapter XI.

ω Radians per second of elementary alternator, in Chapter I., etc. $= 2\pi\sim$

$\sim$ Revolutions per second of elementary alternator, in Chapter I.

Complete reversals per second of alternating current and voltage.

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ALTERNATING CURRENT DESIGN

CHAPTER I

ALTERNATING CURRENTS

THE simplest form of alternator possible would be a single conductor supported parallel to a shaft by radial arms and revolved in a uniform magnetic field. It is worth while to study such an arrangement and the laws which can be deduced from its behaviour before considering the more practical forms of alternating current generators (Fig. 1).

If the length of the conductor parallel to the shaft be l centimetres, that of the radial arms r cms., the peripheral speed of the conductor V cms. per second, and the uniform magnetic field H lines per square centimetre, then the maximum electro-motive force generated in the conductor will be $H \,.\, l \,.\, V \times 10^{-8}$ volts. There is no E.M.F. in the shaft or in the radial supporting arms because they cut no lines of force.

If we call the revolutions per second $\sim$ and the radians per second ω, then $\omega = 2\pi\sim$ and $V = 2\pi r\sim = \omega r$. So that the maximum E.M.F. $E = Hl\omega r \times 10^{-8}$ volts.

But $l \times r$ is the area of the coil in cms². and $H . l . r$ is the maximum number of lines of force ever through the coil; calling these N, the maximum E.M.F. $E = \omega . N . 10^{-8}$.

This is one of the most universal relations in the whole of alternating current work; whenever lines of

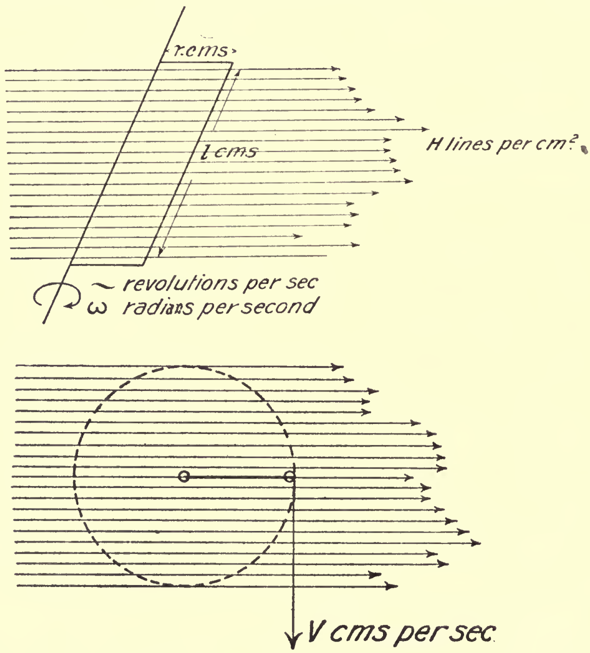

Fig. 1.

force through a coil vary from a maximum N at the rate of ∼ complete reversals per second, then the maximum E.M.F. in each turn of that coil is $\omega . N . 10^{-8}$ where $\omega = 2\pi\sim$. This is true however the lines may be varied, either by revolving the coil, or revolving the field, or magnetizing an iron core which passes

through the coil, or if the lines merely link the coil due to current in the coil itself. It is true whether the lines of force cause the E.M.F., or whether the E.M.F. in being applied to a coil sends such a current through it as will magnetize for that flux N, so that, neglecting only the volts lost in resistance, the reading of a voltmeter is always a measure of the flux.

Returning to the elementary alternator, it is seen that at the instant when the E.M.F. is a maximum the number of lines of force threading the coil is zero and *vice versâ*, *i.e.* that the maximum of the lines through the coil and that of the E.M.F. in the coil are separated by a quarter of a period, or 90 degrees. This result is also true of all cases, just as the former one was.

The E.M.F. at any other position of the coil will be proportional to that component of V which is at right angles to the field, the other component not cutting lines. This active component is $V \sin \theta$, where θ is the angle between the coil at any instant and the coil when the maximum number of lines pass through it, *i.e.* when the E.M.F. is zero. At other times the instantaneous value of the E.M.F. is $E \sin \theta$. This is sometimes written $E \sin (\omega t)$, where ω is the angle in radians turned through per second and t is the number of seconds elapsed since the beginning of movement. ωt is thus an angle like θ, but unlike θ it can be any number of whole revolutions plus any fraction of a revolution. If the coil was not right across the lines at the beginning, but inclined to that position at any

angle α, then to be quite accurate the instantaneous value of the E.M.F. is written as $E \sin(\alpha + \omega t)$.

For these reasons the curve representing the variation of E.M.F. with time is called a "sine wave," and, without entering into a mathematical discussion of its properties, we can take a few of them on trust. Most of the usefulness of electro-motive force for purposes of doing work depends on the square of the E.M.F., so that if the E M.F. is alternating, it is the square root of the mean square which is then required, and which is measured on a voltmeter; for a sine wave this R.M.S. value, as it is written, is the maximum value divided by $\sqrt{2}$. Sometimes, however, we require the simple average current over half a period, and this is the maximum value divided by $\frac{\pi}{2}$.

It will be noticed that in the foregoing the production of an E.M.F. is sometimes attributed to a conductor cutting lines of force, and sometimes to the rate of change of lines linking the circuit, and there are nearly always these two ways of looking at the phenomenon. In some cases one is the more convenient method, and in others the other, but oftener the two points of view together give the best perspective.

Now let this E.M.F. send a current through a second coil having a resistance of R ohms and a self-induction of L henries, and let the maximum value of the resulting current be I amperes. The current I flowing through the resistance R will give rise to a voltage R . I, but it will also give rise to a number of

lines of force linking the coil, the maximum value of which will be $L . I . 10^8$, for L is by definition of the unit of self-induction the number of 10^8 lines linking the circuit for each ampere round the circuit. These lines give rise to an E.M.F. of $\omega . L . I$, which we have already seen will be 90 degrees behind the current. The E.M.F. $R . I$ is in phase with the current, that is, has its maximum value at the same instant as the maximum current.

The value of the current will so adjust itself that

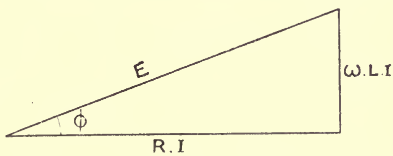

FIG. 2.

the resultant of these two will equal the impressed E.M.F. So that—

$$E = \sqrt{(RI)^2 + (\omega LI)^2}$$

or

$$I = \frac{E}{\sqrt{R^2 + L^2\omega^2}}$$

The root $\sqrt{R^2 + L^2\omega^2}$ is the impedance of the circuit and takes the place of the plain resistance in direct current work.

Now, instead of the circuit having resistance and self-induction, let it have resistance R and capacity F farads; the capacity of a condenser being the amount of electricity in coulombs required to charge it to a potential of one volt, a flow of one coulomb per second being called an ampere.

Let Q be the maximum quantity of electricity ever in the condenser at one time. This will occur when the current has been flowing in one direction for as long as possible and is just going to reverse, and therefore equals zero.

The potential at the condenser will then be a maximum and equal to Q divided by F, so that it is seen that the maximum potential is 90 degrees from the maximum of current.

Q is the quantity of electricity that flows into the condenser during one quarter of a wave, and as there are $\sim$ waves per second the time taken is $\frac{1}{4\sim}$ seconds; the average current is therefore $4\sim Q$ amperes. This average current is equal to the maximum divided by $\frac{\pi}{2}$; therefore

$$I = \frac{\pi}{2} \times 4\sim Q = 2\pi\sim Q = \omega Q$$

The potential of the condenser $= \frac{Q}{F} = \frac{I}{\omega F}$. As before there is an E.M.F. R . I in phase with the current, and the resultant of these two at right angles must equal E, so that—

$$E = \sqrt{(RI)^2 + \left(\frac{I}{F\omega}\right)^2}$$

or

$$I = \frac{E}{\sqrt{R^2 + \frac{1}{F^2\omega^2}}}$$

the denominator being the impedance of the circuit.

Next consider a circuit having both resistance, self-induction, and capacity. It follows from the above that the potentials at the terminals of the two latter, being both at right angles to the current, are themselves in the same straight line, and it only remains to determine if they are in the same or opposite directions.

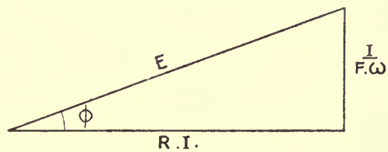

Fig. 3.

Consider the instant when the current is just reversing. It has been flowing into the condenser up to now, which is therefore full, and on the current reversing will begin to discharge, aiding the recently reversed current. The lines of force linking the part of the circuit having self-induction, on the contrary, will be just increasing and building up an E.M.F. in opposition to the increasing current.

This shows that the two E.M.F.'s are in opposite directions at the terminals of the capacity and self-induction, and therefore

$$I = \frac{E}{\sqrt{R^2 + \left(L\omega - \frac{1}{F\omega}\right)^2}}$$

which is the general expression for the flow of alternating currents.

It is worth while to notice that whichever of the last two terms is the greater, the bracket is always positive ;

it, however, vanishes when $L\omega = \frac{1}{F\omega}$, when the expression becomes one of Ohm's Law merely. This means that for every circuit having both self-induction and capacity there is one frequency at which the effects of both vanish and the circuit behaves as if it contained

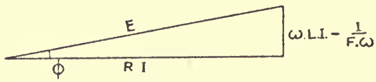

FIG. 4.

resistance only. If a means exists of supplying the circuit with a variable frequency, this forms a ready means of measuring either self-induction or capacity, the value of the other being known, as the current suffers an extremely rapid variation as the frequency nears the critical value.

The foregoing work also defines the power factor, which is the cosine of the angle between the current and the impressed E.M.F. The tangent of this angle is, in the case of resistance and self-induction alone, $\frac{L\omega}{R} = \frac{2\pi \sim L}{R}$, so that the power factor of a circuit is seen to decrease as either the self-induction or the frequency increase or as the resistance decreases. In the case of resistance and capacity

$$\phi = \tan^{-1} \frac{1}{2\pi \sim FR}$$

and the power factor increases as either the frequency, capacity, or resistance increase.

In the most general case of a circuit containing resistance, self-induction, and capacity,

$$\phi = \tan^{-1}\frac{1}{R}\left(L\omega - \frac{1}{F\omega}\right)$$

and the power factor will be either leading or lagging according as $\frac{1}{F\omega}$ is greater or less than $L\omega$; when these are equal the current will be in phase with the voltage, *i.e.* the power factor will be unity.

CHAPTER II

ARMATURE REACTION

In the last chapter the effect of the current on the behaviour of the alternator itself was neglected. This is, however, a very important matter which we will now consider. For this purpose a very simple vector diagram will be used. Fixing our attention for the moment on a two-pole revolving field alternator, let us, as it were, point with vectors to the maximum values of the current, voltage, fluxes, etc., as they revolve round the centre; these vectors by their length will also, to some convenient scales, represent the magnitude of the quantities involved.

It is seen that this system of picturing what is happening in the alternator by pointer vectors represents the relation between the various quantities *in space*, and for this reason must not be confused with any other system of vectors which might endeavour to represent this mutual relationship *in time*. The angle whose cosine we call the power factor is an example of the former notation, in that it represents the space separating the maximum values of the voltage and current; to translate such an angle, expressed in degrees, into seconds of time, it is necessary to divide by 360

times the frequency. Another difference should also be pointed out here, which is that the voltage is taken as residing in the active conductors themselves, and not at the hypothetical centre of a coil formed by two sets of active conductors and their end connections.

The most important thing that goes round the alternator is the stator flux, namely, that flux which

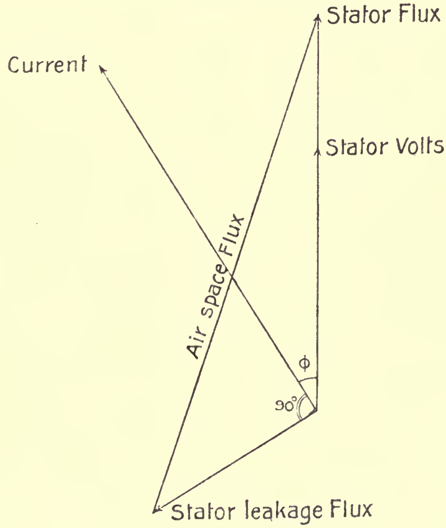

Fig. 5.

actually cuts the stator conductors and enters the iron at the back of the stator slots. It is this flux which makes the stator volts, all of which volts are measured by a voltmeter at the terminals of the machine, excepting only those lost in stator resistance. It is worth while to insist on this statement, as there is so often erroneously supposed to be some larger flux than this in the stator.

As it is this flux which, by cutting the stator conductors, makes the stator volts, these latter are in phase with the former and proportional to it. It follows that the stator flux and terminal voltage can be represented by different lengths of the same vector, measured off each to its appropriate scale.

The maximum stator current will be at an angle ϕ

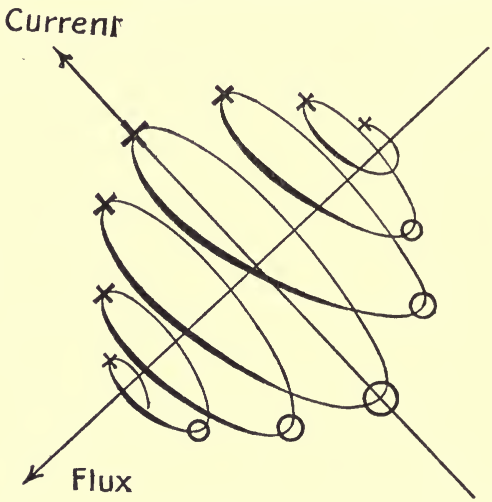

Fig. 6.

to the terminal voltage, when $\cos \phi$ is the power factor of the outside circuit.

The next flux to consider is the stator leakage flux, *i.e.* that flux which surrounds the stator conductors simply from their own magnetizing force. That this flux is at right angles to the position of the maximum current is shown by the sketch (Fig. 6).

The stator leakage flux runs along the roofs of the stator teeth and crosses the air space to the magnets;

at least, this is the final result. If the fluxes could be built up separately, the leakage flux would first of all travel along the roofs of the stator teeth and enter the stator, and return by the iron at the back of the stator; then the magnet flux would cross the air space, and part of it, combining with the leakage flux, would form the true stator flux at the back of the stator conductors, and part of it would return to the magnet circuit *viâ* the roofs of the slots, combining with the other part of the leakage flux.

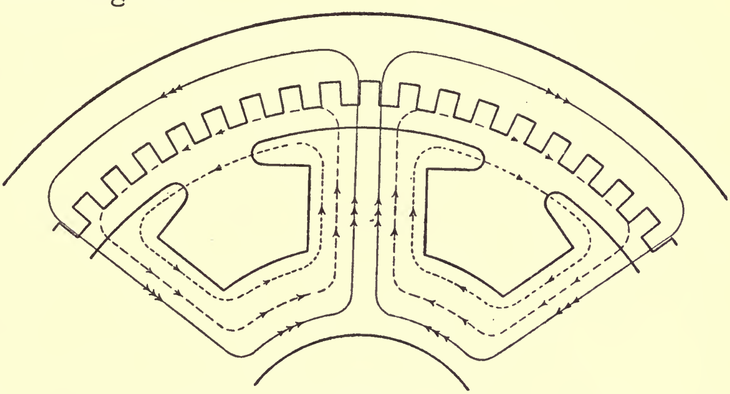

Fig. 7.

There is also that flux which exists in the magnet circuit but does not cross the air space, leaking from pole to pole of the magnets; this is the magnet leakage flux, which is generally somewhat mechanically dealt with by means of a leakage coefficient.

So it comes about that the magnet circuit proper has to provide three sets of lines of force, one which never crosses the air space but leaks from pole to pole, another which crosses the air space and leaks over the

roof of the stator slots, and a third which, cutting the stator conductors, enters the stator iron and constitutes the working stator flux. This last is the only flux which cuts conductors and therefore which produces volts. If a search coil winding were supported just clear of the pole tips, this would measure a voltage proportional to the air space flux, but as such a winding does not usually exist, it is a mistake to translate these other fluxes into volts at all, it being much simpler to treat them as fluxes.

These various fluxes are not, however, all in phase, *i.e.* do not have their maximum values simultaneously, and so cannot be added arithmetically. The vector diagram shows their relative magnitude and phase. The air space flux is the resultant of the stator flux and the stator leakage flux. The total rotor flux is obtained from the air space flux by multiplying this latter by a waste field coefficient, although, strictly speaking, the magnet waste field or leakage flux is proportional to the excitation and inversely proportional to the reluctance of the leakage paths, and is not connected with the main flux in any very simple way.

These three fluxes having been determined, and the areas of the magnetic paths calculated, a synthesis can be made in the usual way, but using the three different fluxes for the stator, the air space, and the magnet circuit respectively. This synthesis will give the ampere turns required to get the full load fluxes through the magnetic circuit, and it now remains to add to these an extra amount to overcome the demagnetizing effect of the

stator currents. To do this draw a vector, representing in length, to some convenient scale, the ampere turns from the combined synthesis, and make its direction parallel to the vector representing the air space flux in the flux diagram (Fig. 5). The demagnetizing stator ampere turns are at right angles to the stator current and parallel to the stator leakage flux (see Fig. 6); drawing these to the same scale of ampere turns from the same

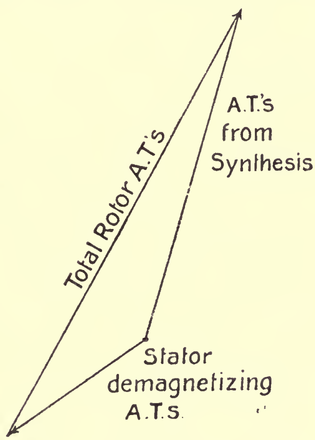

Fig. 8.

point as the ampere turns from the synthesis, the resultant of the two gives, to the same scale, the total ampere turns required on the rotor for full load at the particular power factor chosen.

Let us now consider the actual numerical values of the various quantities we have been using. Firstly the stator flux; this is obtained from the total volts by multiplying these latter by $\sqrt{2}$ and 10^8 and dividing by $2\pi\sim$ and the turns in series. The total volts are

simply the terminal volts added to those lost in the stator resistance; strictly speaking, vector addition should be employed for power factors less than unity, as the lost volts are in phase with the current, and this in reality throws the stator flux slightly out of phase with the terminal volts. In practice, however, the volts lost in resistance are so small a fraction of the terminal volts that this refinement is not worth putting into force, and the total volts are taken as the arithmetical sum of the terminal and lost volts.

The stator leakage flux may be arrived at in various ways, the first of which consists in consulting the results of the many excellent published experiments which give the leakage lines of force per inch length of slot per ampere in the slot for various different shapes of slots. The figure for this leakage flux varies from about 50 in parallel to 100 in roofed slots; this has of course to be multiplied by the length of the slot and by the current flowing in the conductors in the slot. Some allowance should also be made for leakage lines round the end connections, this again being affected by whether all the end connections from one pole are collected together so that each is cut by the lines made by all the others, or whether the end connections are more separated, being cut only by their own or immediate neighbours' lines.

The rotor waste field coefficient, though depending on many other things than those mentioned in the following formula, may, in the absence of more definite experimental data, be approximately represented by

$1 + \sqrt{\frac{0 \cdot 2 \times \text{poles}}{\text{diameter}}}$; the magnet flux being the air space flux × w.f.c., and the diameter being that of the air space in inches.

The next quantity to evaluate is the demagnetizing effect of the stator current. In a single-phase stator winding the maximum value of the ampere turns per pole is $\sqrt{2}$ × R.M.S. current × turns per pole; that the magnetic effect of this winding may be split up into two equal parts revolving round the stator in opposite directions with the speed of the field magnets is susceptible to mathematical proof as well as to experimental verification. That part which revolves in a direction opposite to that of the magnets has no resulting demagnetizing effect, producing merely a surge in the flux of twice the frequency of the alternator; that half which revolves at the same speed as the magnets and in the same direction is consequently stationary with regard to the magnet poles and exercises a demagnetizing effect on them, in amount equal to half the maximum ampere turns, and in phase, at right angles to the stator current. In multiphase windings the total turns per pole of all phases are of course taken, and the demagnetizing ampere turns are $\frac{\sqrt{2}}{2}$ × R.M.S. current per phase × total turns per pole on all phases.

We have now all the data, not only to determine the requisite strength for the magnet winding of an alternator, but also to predict its voltage regulation at all power factors and loads.

The "Inherent Regulation" of an alternating current generator is defined by the British Standards Committee as the rise in terminal voltage on full load being thrown off at the specified power factor, both the speed and the excitation being kept unaltered. This rise can be kept down by two methods, firstly by making the increase of magnetizing force from open circuit to full load small, which may be done either by keeping the stator leakage flux, or the stator ampere turns per pole, or both, low; and secondly, whilst allowing the full load magnetization to be largely in excess of that required for open circuit, the inductions in some or all of the magnetic circuit may be normally so high that the large number of ampere turns set free on throwing off the load may be unable to produce more than a slightly increased flux, and therefore volts, on open circuit.

In most cases the first method mentioned will give rise to an alternator which requires less attention in actual running, but the latter method will, in general, make the cheaper design to build, and would be oftener employed by the designer when working to a given inherent regulation specified in this way, were it not for a certain element of risk which is always present in using these high inductions—that a small error may be made in estimating, say, the stator leakage flux or the rotor waste field coefficient, thus making it difficult or impossible to obtain the required voltage, especially at low power factors.

Another method of defining the regulation is by

the drop in terminal voltage from open circuit to full load. This is framed to prevent the obtaining of good regulation by high inductions as above, but is, however, unsatisfactory from other reasons, one of which is that "full load" can never be obtained with the open circuit excitation; in many alternators full load current even would not be reached if the alternator were short-circuited with the open circuit excitation. Obviously, the regulation should not be specified or tested under conditions so far removed as this from actual practice. All interests would be safeguarded by specifying the rise in terminal voltage on throwing off full load, together with the ratio of full load to open circuit excitation.

CHAPTER III

RELATION OF DIMENSIONS TO OUTPUT

One of the most obvious limitations which imposes itself on all running machinery, whether for direct or alternating current, is the density of current round the air space, the number of amperes in unit arc of circumference.

In this way can be expressed, not only the electro-magnetic effect of so much concentrated current, but also the physical possibility of packing the conductors carrying such current into the space at our disposal.

Taking the latter limitation first, it is readily seen that 1000 amperes per inch of circumference, combined with, say, 1000 amperes per square inch of conductor, would require a depth of winding not possibly less than an inch, and with teeth and slots of equal width at 50 per cent. space factor in the latter, 4 inches deep.

Not less is it a limit to armature reaction, for the effect of the armature current on the magnet system is obviously proportional to the concentration of the former.

Now, the term "amperes per unit arc of circumference," although expressing just what is wanted, is

cumbrous, partly because it is the diameter which is usually measured, not the circumference, and also because there seems to be a disinclination to think of current as disassociated from the conductor it is flowing in; so that the expression has gone through the forms "ampere conductors per unit of circumference," "ampere conductors per unit of diameter," to "ampere turns per inch diameter," the last change from ampere conductors to ampere turns being particularly indefensible, as it is not in the effect of a closed ampere turn that the phenomenon is being studied at all, turns being merely equivalent to "conductors divided by two."

Not only do the ampere turns per inch diameter form a limit to every class of revolving electrical machinery, but in all the value of this constant is nearly alike, varying from about 800 to 1200, according to size, etc.

The magnetic induction in the air space is another quantity which it is not advisable to vary far from certain prescribed limits, which are, on the one hand, the proper use of material to the best advantage, and, on the other, the maximum allowable induction in the teeth and the limits to magnetizing force on the rotor. The proper compromise between these two may lie somewhere about a maximum induction of 8000 lines per square centimetre of air space.

Taking this figure in conjunction with one for the ampere turns per inch diameter of 800, we get that the square of the diameter multiplied by the axial

length of the alternator is equal to the output at one revolution per minute divided by 0·031. For let

E = R.M.S. volts
C = R.M.S. amperes
N = lines of force per pole
T = total turns on stator
R = revolutions per minute
D = air space diameter in inches
L = axial length in inches
P = number of poles.

Assuming a sine wave distribution of lines over the air space

$$\text{the maximum induction} = \frac{\pi}{2},$$

$$\text{the average} = \frac{\pi}{2} \times \frac{PN}{\pi D l \times 6{\cdot}45} = 8000 \text{ lines per cm}^2.$$

from which

$$PN = Dl \times 2 \times 6{\cdot}45 \times 8000$$

The ampere turns per inch diameter $= \dfrac{CT}{D} = 800,$

or
$$T = \frac{D}{C} \times 800$$

Now
$$N = \frac{\sqrt{2}\, E \times 10^8}{2\pi \sim T}$$

and
$$\sim = \frac{PR}{120}$$

from these two
$$PN = \frac{E}{RT} \times \frac{\sqrt{2} \times 120 \times 10^8}{2\pi}$$

Putting in the value of T from above, and equating to the first value of PN, we get that

$$\frac{EC}{R} = D^2 l \times 0{\cdot}031.$$

The similar constant for direct-current generators with the same ampere turns per inch diameter, reactance volts of 5, and volts per commutator bar of 10, is 0·034.

Besides these two more or less theoretical limitations there are, in alternating-current generators, certain limitations arising out of the least *convenient* pole pitch which can be used for internally revolving magnets. One would not willingly make the core of the magnet pole less than 3 inches circumferentially; putting $1\frac{1}{2}$ inches of winding on each side of this and allowing 1 inch for insulations and clearance, makes a pole pitch of 7 inches. This can be expressed by saying that the diameter must not be less than the number of poles multiplied by 2·2.

The peripheral speed of the magnets imposes a limit in the other direction. If we limit this to, say, 8000 feet per minute, by simple arithmetic the diameter cannot be more than the number of poles multiplied by 250 and divided by the frequency; which gives, at $\sim$25, 10 times the number of poles, and at $\sim$100, 2·5 times. Comparing this last figure with the statement in the preceding paragraph that the diameter should not be less than 2·2 times the poles, it is seen, what is indeed found to be the case, that at frequencies above 100 either the poles would be crowded or the peripheral speed high.

CHAPTER IV

EXAMPLE OF THE DESIGN OF AN ALTERNATOR

To illustrate the foregoing, we will now proceed to the design of an alternating current generator to fulfil the following specification: Output, 250 kilowatts at any power factor from unity to 0·8; 1000 volts 3-phase 50 ~, 375 r.p.m.; overloads, 25 per cent. for 2 hours, 50 per cent. for 5 minutes. Temperature rise not to exceed 40° Centigrade after 6 hours at 250 KW. at 0·8 power factor. Inherent regulation, not more than 6 per cent. rise at p.f. 1, and 20 per cent. rise at p.f. 0·8 when full load is thrown off, keeping the speed and excitation unaltered.

Star wound, the volts per phase will be 577, the current per phase p.f. 1 will be 144 amperes, and p.f. 0·8 180 amperes; 25 per cent. overload at the lower p.f. is 225, and 50 per cent. 270 amperes.

Number of poles is 16 for 50 ~ at 375 r.p.m.

First, as to diameter, the various guides given in the last chapter are: Firstly, the D^2l formula for a length of 10 inches, which would give for 312·5 K.V.A., a diameter of 52 inches; secondly, the least diameter, from reasons of crowding magnets, would be 48 inches; and, thirdly, the greatest diameter, from questions of

peripheral speed, would be 82 inches. Obviously, it is not good practice to approach too near to either of the last two limits, and so, in the absence of any guide afforded by the nearest pattern in stock, we will choose a diameter of 60 inches bore of stator plates.

The total turns to give 800 ampere turns per inch diameter at 60 inches would be 266, or 89 per phase. For a two-plane winding on the stator there cannot conveniently be less than two conductors per slot, also there must be a whole number of slots per pole per phase. Making this five gives 80 turns per phase, and 240 as the total number of slots.

Stator winding, 180 amperes at, say, 1800 amperes per square inch, gives 0·1 square inch for the area of the copper. Try $0{\cdot}4'' \times 0{\cdot}25''$ insulated with $0{\cdot}05''$ of micanite all round. The covered conductor will be $0{\cdot}5'' \times 0{\cdot}35''$. A slot $0{\cdot}4''$ wide will allow of a slot lining of leatheroid to protect the micanite from the edges of the plates. Two $0{\cdot}5''$ conductors and a strip of hard wood will go in to a depth of $1{\cdot}25''$. So that we have 240 slots $1{\cdot}25'' \times 0{\cdot}4''$. The next step is to estimate the resistance of the stator circuits in order to get the total volts and thus the stator flux. This involves knowing the length of the stator plates parallel to the shaft; assume this to be $10''$. The end connections may likewise be assumed to form the sides of an equilateral triangle with the pole pitch as base. The pitch of 16 poles at $60''$ diameter is $12''$, so that the length of each turn will be about $2 \times 10 + 4 \times 12 = 68''$. The resistance of one phrase of 80 such turns, allowing a

temperature of 60° C. would be 0·042 ohm but for the fact that 20″ of the conductor is embedded in iron and cut by its own leakage flux, which produces a local current which circulates along the top half of the embedded conductor and back in the lower half; this eddy current combines with the main current, adding in the top half and subtracting in the lower half of the conductor, the net result being that the current appears to be crowded up into the top edge of the conductor, thus causing a larger ohmic drop than if it distributed evenly throughout the section. Mr. M. B. Field has published a curve in which the increase of ohmic resistance of the embedded conductor is plotted against a quantity "*mb*" (see the *Journal of the Institution of Electrical Engineers*, vol. 37, p. 101). $mb =$ area of the conductor in

$$\text{sq. in.} \times \sqrt{\frac{0\ 13 \times \sim}{\text{width of conductor}'' \times \text{width of slot}''}}$$

In the present case *mb* would equal 0·8; referring to the curve we find that the resistance of the bottom conductor will be increased 4 per cent., and that of the top conductor 30 per cent. This, of course, only applies to two lengths of 10″ each out of a total of 68″, so the whole resistance will be increased 5 per cent.

The volts lost in resistance at the normal current of 180 amperes will therefore be 8 per phase, making a total of 585, which corresponds to a stator flux of

$$\frac{\sqrt{2} \times 585 \times 10^8}{2\pi \times 50 \times 80} = 3{\cdot}3 \times 10^6 \text{ lines per pole.}$$

The area required for the teeth to carry this flux at a maximum induction of 17,000 lines per cm^2. is 30 sq. in.

If the width of the pole face is such that the winding of one phase occupies the gap between the poles at one

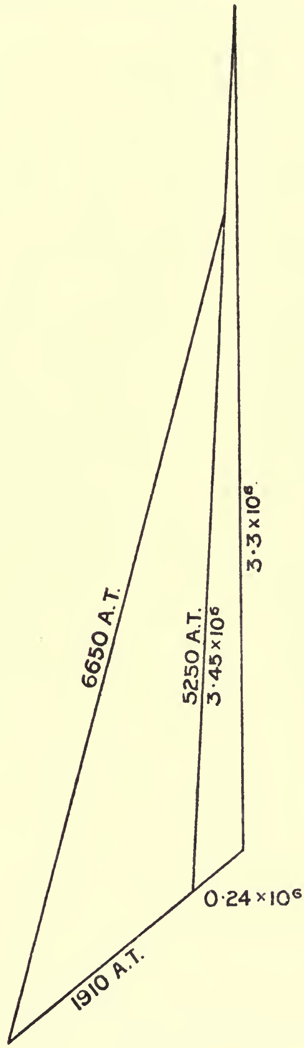

Fig. 9.

instant, then there are 11 teeth to carry the lines from

each pole. The pitch of 240 teeth at 60″ diameter is 0·79″, the slot is 0·4″ of this, leaving 0·39″ for the tooth; the length of iron required is therefore the 30 sq. in. divided by 11 times 0·39″ = 7″.

Using plates 0·014″ thick for the stator, and insulating them with 0·001″ varnish each side, the insulated plates will measure 8″; putting three $\frac{1}{2}''$ ventilation spaces into this makes 9·5″ overall length of core plates.

The area required for an induction of say 8000 at the back of the slots, is 32 sq. in., which divided by the net length of iron gives 4·6″ depth radially. The outside diameter of the stator plates would then be $60 + 2 \times 1{\cdot}25 + 2 \times 4{\cdot}6 = 71{\cdot}7''$; make this 72″, which gives an induction of 7700 lines per cm².

The slot leakage flux, assuming 50 lines per ampere per inch length of slot, at a current of 180 amperes, amounts to $50 \times 180 \times \sqrt{2} \times 9{\cdot}5 = 0{\cdot}24 \times 10^6$.

The angle whose cosine is 0·8 is 37 degs., so that the stator flux and the stator leakage flux are at an angle of 90 + 37, or 127 degrees. Drawing the two vectors $3{\cdot}3 \times 10^6$ and $0{\cdot}24 \times 10^6$ at this angle, the resultant is found to be $3{\cdot}45 \times 10^6$, which is the flux in the air space.

The waste field coefficient, indicated by the formula in Chapter II would be 1·22, say 1·25 for safety. The rotor flux is then $4{\cdot}3 \times 10^6$. To accommodate this in steel at $B = 17{,}000$ needs 39 sq. in. 5″ × 9″ with semicircular ends gives 39·6 sq. in. and 16,700 lines per cm². Before settling on these dimensions for the pole, it is

wise to see if they allow sufficient room for the magnet winding. Assuming a 6″ length for the pole, and $\frac{1}{4}$″ a side for the clearance between stator and rotor, the outside diameter of the yoke is $47\frac{1}{2}$″, making the pole pitch there 9·3″. Allowing $\frac{1}{4}$″ clearance between coil and pole and $\frac{1}{2}$″ between coils, the minimum depth of the coil is 1·7″, and assuming a depth of 1″ for the pole

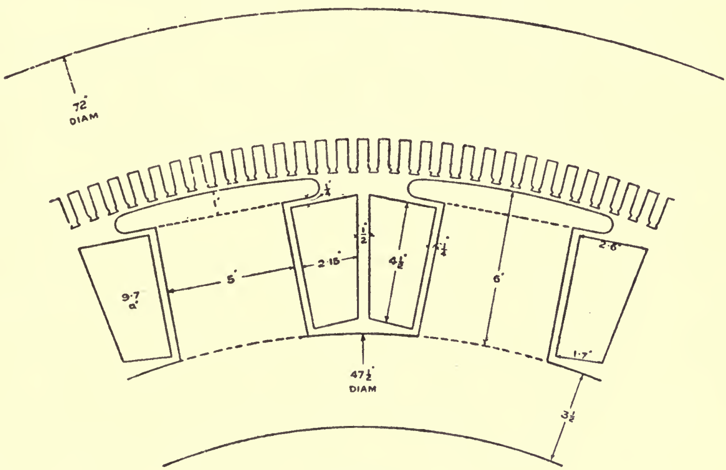

Fig. 10.

tip the maximum depth of the coil is 2·6″ and the height 4·5″, which gives an area for winding of 9·7 sq. in., which should be sufficient (Fig. 10).

The thickness of the pole tip next deserves attention. The pole arc has already been settled at two-thirds of the pole pitch, or 7·8″. The flux from this to the air space is, we have seen, $3{\cdot}45 \times 10^6$ lines, whilst the flux in the magnet core is $4{\cdot}3 \times 10^6$. Two assumptions are now made, each on the safe side; firstly, that the

flux to the air space is uniformly distributed over the pole face, and secondly that all the rotor waste field passes through the pole tips, so that the flux which does not do so is $\frac{5}{7{\cdot}8}$ of $3{\cdot}45 \times 10^6 = 2{\cdot}2 \times 10^6$. The rest, or $4{\cdot}3 - 2{\cdot}2 = 2{\cdot}1 \times 10^6$ lines, must pass into the pole tips from the magnet core; at 18,000 B this requires 18 sq. in., or 9 sq. in. each side; the length of the pole tip is $9\frac{1}{2}''$, so that $1''$ thickness at the centre will be satisfactory.

The yoke ring, if of cast iron may be worked at about 8000 lines per cm^2., and would then require an area of 42 sq. in. or say $12'' \times 3\frac{1}{2}''$. If this is done, some provision must be made for the lines, which are at an induction of 17,000 in the steel, to enter the cast iron at not more than half this. This may be done by providing the steel poles with enlarged bases where they abut against the cast iron; these could be $9'' \times 9'' \times 1''$ thick in this case. Or again, the steel poles could be recessed into the cast iron. In the former case the pole tip would have to be separate, and might very well be laminated in the same plane as the stator plates.

This finishes the outward design with the exception of the magnet winding; for this a synthesis of the magnetization is required. This differs from the ordinary only in the use of the three fluxes already obtained for the stator, air space and rotor circuits respectively. The area of the teeth is taken as that at one-fifth of their length from the small end, and the area of the air is one-fifth of the way between the pole face and the tops of the teeth,

i.e. four times the pole face area is added to the minimum tooth area and the sum divided by 5. This process has no theoretical basis, and its only justification is that it usually checks very closely with the observed facts.

SYNTHESIS OF MAGNETIZATION AT FULL LOAD P.F. 0·8.

	Magnetic circuit.		Flux $\times 10^6$.	B lines per cm².	H per cm.	$H \times l$ C.G.S. units per 2 poles.
	Length cms.	Area cms².				
Stator core × 2 ...	33·5	430	3·3	7,700	2	67
Teeth $\frac{1}{3}$	6·35	197	3·3	16,800	36	228
Air space $\frac{1}{3}$	1·27	420	3·45	8,210	8210	10,430
Magnet cores ...	31·0	256	4·3	16,800	61	1,890
Yoke × 2	20·0	540	4·3	8,000	26	520

Magnetizing force = 5,250 A.T.'s per pole = 13,135

To these 5250 ampere turns per pole must be added, at the proper angle, the ampere turns to compensate for armature reaction; these, from Chapter II. $=\frac{\sqrt{2}}{2} \times 180 \times \frac{240}{16} = 1910$ A.T.'s. Putting these on to the vector diagram, Fig. 9, measuring one off on the direction of air space flux and the other on the direction of stator leakage flux, we arrive at the result that 6650 ampere turns are required per pole on the rotor when the alternator is doing 1000 volts 180 amperes at 0·8 power factor.

But the alternator has also to give for five minutes a 50 per cent. overload; the rotor winding will therefore have to magnetize for this.

The increase in the stator flux brought about by the increased resistance drop may be neglected, but the stator leakage flux is increased 50 per cent. to $0{\cdot}36 \times 10^6$

lines; this increases the air space flux to $3{\cdot}53 \times 10^6$ and the rotor flux to 4·41. If the combined synthesis is worked out for these new fluxes, the ampere turns are found to have increased from 5250 to 5550 per pole. The demagnetizing A.T.'s are increased 50 per cent. to 2860, which on the vector diagram results in 7750 A.T.'s total for 50 per cent. overload at a p.f. of 0·8.

The rotor winding should give, therefore, at least 8000 A.T.'s when warm, for a few minutes, and 6650 A.T.'s under the temperature rise specification.

The mean depth of the magnet coil is 2·15″. This is wound round a core $9'' \times 5''$ with semicircular ends, with $\frac{1}{4}''$ clearance from the steel; this makes the length of the mean turn $2 \times 4 + \pi \times 7{\cdot}65 = 32''$.

Now the ampere turns are dependent on the area of the wire only and not on the number of turns, so that if we excite from a 100-volt circuit the resistance of one turn per pole must be such as to allow 800 amperes to flow; *i.e.* $16 \times 32 = 512$ inches must have a resistance warm of 0·0125 ohm, so that the area required is 0·0315 sq. in. In round wire the diameter would be 0·2″, or double cotton-covered 0·216″. This at 1000 amperes per sq. in. will carry 31·5 amperes, which current gives the required full load excitation of 6650 A.T.'s with 210 turns. The space required for this would be $210 \times 0{\cdot}216^2 = 9{\cdot}8$ in^2. The space available is 9·7 in^2., into which 200 turns of such wire will go nicely.

The resistance of 16 poles in series will be 2·17

ohms cold, or 2·5 ohms at 60° C. The loss in the magnets at full load will be $2{\cdot}5 \times 33{\cdot}25^2 = 2{\cdot}75$ KW., which is 0·88 per cent. of the K.V.A. output.

Before the entire behaviour of the alternator can be predicted an open circuit magnetization curve must be worked out. This is done on the same lines as the previous synthesis, but with no stator leakage flux, the same waste field coefficient being used for the magnet circuit. Four points, if well chosen, will be sufficient to draw this curve through. Take 2, 3, 3·5, and 4 million lines in the stator, corresponding to 615, 920, 1080, and 1230 line volts at 375 r.p.m. respectively.

The areas and lengths of the magnetic circuits are, of course, the same as for the last synthesis, and are not here repeated.

Open Circuit Synthesis.

Line volts		615	920	1080	1230
Flux $\times 10^6$		2	3	3·5	4
B and H,	Stator	4,650 – 1	7,000 – 1·5	8,150 – 2	9,300 – 2·5
	Teeth	10,100 – 3	15,200 – 13	17,700 – 82	20,200 – 300
	Air	4,760	7,140	8,330	9,520
	Magnets	9,750 – 3·5	14,600 – 17	17,000 – 68	19,500 – 300
	Yoke	4,630 – 13	6,950 – 20	8,100 – 27	9,250 – 36
$H \times l$,	Stator	33	50	67	85
	Teeth	19	82	520	1,900
	Air	6,050	9,070	10,580	12,090
	Magnets	108	527	2,110	9,300
	Yoke	260	400	540	720
C.G.S. per 2 limbs		6,470	10,129	13,817	24,095
A.T.'s per pole		2,590	4,050	5,530	9,640

Fig. 11 shows the result, line volts at 375 revolutions per minute being plotted against ampere turns per pole.

This curve shows that the full load 0·8 power factor excitation of 6650 A.T.'s gives on open circuit 1150 volts, or 15 per cent. rise on throwing off this load, which is 5 per cent. within the guarantee.

Open Circuit Magnetization Curve.

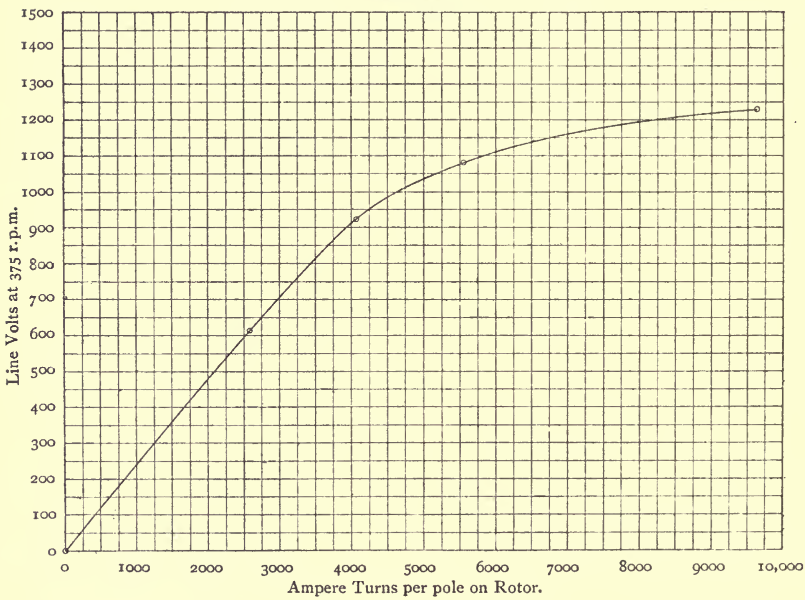

Fig. 11.

Allowing a 3 per cent. rise in speed on open circuit, the excitation per 1000 volts is seen to be 4400 A.T.'s ; to get this from the 100 volt supply would need a resistance of 2·36 ohms in series with the magnets, graduated to carry a current of from 22 amperes when all in circuit to 40 amperes on the last point.

We have already enough data to draw the curve,

which is very nearly a straight line, between the current per phase and the ampere turns required on the magnets to maintain 1000 volts at 0·8 power factor at 375 r.p.m. The points are these: No current, 4650 A.T.'s; 180 amperes, 6650 A.T.'s; 270 amperes, 7750 A.T.'s (Fig. 12).

LOAD CURVES.

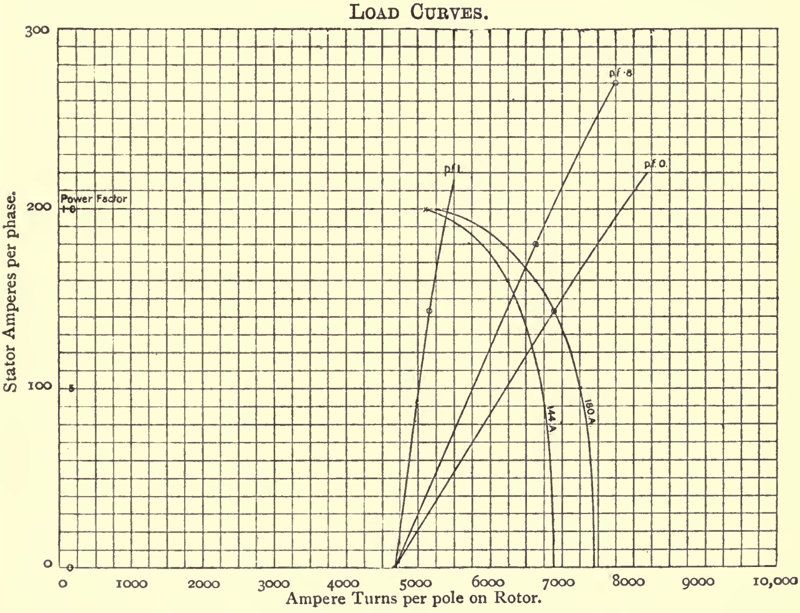

FIG. 12.

At unity power factor, full load current is 144 amperes, the stator flux 3·29, and the stator leakage $0·19 \times 10^6$ lines; these two at right angles result in an air space flux of $3·3 \times 10^6$. As these are so nearly alike, it will be quite accurate to look up $3·3 \times 10^6$ lines, which are equivalent to 1015 line volts, on the open circuit magnetization curve, where it corresponds to

4800 A.T.'s. The demagnetizing ampere turns for 144 amperes are 1540; these two, on the vector diagram, have a resultant 5150 A.T.'s, which is therefore the magnetization required for full load power factor unity.

5150 A.T.'s on the open circuit curve correspond to 1050 volts, or a rise of 5 per cent. on unity p.f., which is 1 per cent. within the guarantee.

It is interesting to see what would happen on zero power factor. Here the stator and stator leakage fluxes would add; taking the 144 amperes the fluxes are $3{\cdot}29 + 0{\cdot}19 = 3{\cdot}48 \times 10^6$ for the air space flux. We have a combined synthesis worked out for $3{\cdot}45 \times 10^6$ lines on the air space, which gave 5250 A.T.'s, so we may take 5350 A.T.'s for 3·48. These again add to the 1540 demagnetizing A.T.'s, making a total of 6890 ampere turns per 1000 volts 144 amperes at zero power factor.

On Fig. 12 are plotted these three curves connecting amperes per phase in the stator with ampere turns per pole on the rotor to maintain 1000 terminal volts at power factor zero, 0·8 and unity respectively. From these can be plotted curves connecting A.T.'s per pole on the rotor with the power factor of some constant current from the stator. Two of these have been drawn for 144 and 180 amperes, they serve to show how very fast the excitation has to be increased for the first small falling away from unity on the part of the power factor; for instance, on the 180 ampere curve, the alteration from unity to 0·85 p.f. is greater than from 0·85 to zero.

It is often necessary to know what current would result if the alternator were short-circuited at its terminals with full load excitation. The converse of this is easier to calculate, *i.e.* the excitation for a certain current on short circuit. As the short-circuit current is very nearly proportional to the excitation, it is immaterial what is the particular current chosen, so take 500 amperes. The terminal voltage being zero, the only flux in the stator is that required to generate sufficient volts to overcome the stator resistance. At 500 amperes this is 22 volts per phase, which requires a stator flux of $0{\cdot}125 \times 10^6$ lines. The stator leakage flux will be $0{\cdot}67 \times 10^6$, the resultant of these at right angles is $0{\cdot}682 \times 10^6$, which corresponds to 208 line volts, which, on the open circuit curve, requires 850 A.T.'s. The demagnetizing A.T.'s for 500 amperes are 5300; the resultant of these two on the vector diagram is 6100. The full load 0·8 p.f. excitation is 6650, so that the short-circuit current will be larger than 500 in that ratio, or 540 amperes. This is exactly three times the normal current of 180.

In calculating the efficiency of an alternator the most difficult of the losses to estimate is that in the stator plates. The theoretical value of the hysteresis and eddy current loss is always largely exceeded, due partly to the imperfect insulation between the plates, partly to the fact that the magnetic lines of force are not always in the plane of lamination and still more to the treatment to which the plates have unavoidably to be subjected during the building up and

winding of the stator. Any filing or rough treatment of the teeth adds very largely to this increased loss.

The designer has, therefore, to fall back on the use of total loss curves, which connect the sum of the hysteresis and eddy current losses per pound of plates with the induction, at some fixed frequency and thickness of plates, at other frequencies the assumption being that the induction may be varied inversely with the frequency for the same total loss per pound. As these curves are drawn from actual measured losses in normal machines, they may be relied on to give a very fair indication of the losses in other cases where the conditions are also normal.

At 50 cycles per second and plates of about 0·015″ thick, the total loss at an induction of 4000 lines per cm^2. may be taken at about one watt per pound; the loss about doubling at 7000, and again doubling to 4 watts per pound at an induction of 10,000 lines per cm^2.

The fact that the induction is higher in the teeth than in the plates at the back of the slots can be roughly allowed for in calculating the weight of plates by not subtracting the weight of the material from the slots, *i.e.* taking the weight of the blanks before stamping out the slots. This, in the case of the alternator under consideration, works out to 2440 pounds. The induction is 7700, which, on the above scale, corresponds to a loss of 2·3 watts per pound, making a total of 5·6 KW. or adding 25 per cent. for windage and friction, 7 KW.

The magnet current for 1000 volts at 375 r.p.m. is

23·25 amperes on open circuit, and can be read off from the curves on Fig. 12 for other loads.

The magnet resistance, allowing a temperature of 60° C., is 2·5 ohms. The stator resistance per phase, allowing the same temperature and also for the "Field" effect, is 0·044 ohm.

EFFICIENCY AT UNITY POWER FACTOR.

At	$\frac{1}{4}$	$\frac{1}{2}$	$\frac{3}{4}$	full	$1\frac{1}{4}$	$1\frac{1}{2}$ load.
Core loss and friction	7·0	7·0	7·0	7·0	7·0	7·0
Stator C^2R	0·17	0·69	1·54	2·75	4·3	6·2
Rotor C^2R	1·44	1·47	1·6	1·66	1·76	1·88
Sum losses	8·61	9·16	10·14	11·41	13·06	15·08
Output	62·5	125·0	187·5	250·0	312·5	375·0
Input	71·11	134·16	197·64	261·41	325·56	390·08
Efficiency	87·9	93·2	94·9	95·6	96·0	96·1 %

AT POWER FACTOR 0·8.

Stator C^2R	0·27	1·08	2·4	4·3	6·7	9·7
Rotor C^2R	1·66	1·99	2·35	2·75	3·22	3·75
Sum losses	8·93	10·07	11·75	14·05	16·92	20·45
Input	71·43	135·07	199·25	264·05	329·42	395·45
Efficiency	87·5	92·5	94·1	94·7	94·8	94·8 %

WEIGHTS AND COSTS OF ACTIVE MATERIAL.

	Material.	Weight in lbs.	Rate.	Cost £.
Stator stampings	M.S.	2200	30/- cwt.	29·5
Stator winding	Cu	520	1/- lb.	26·0
Rotor pole pieces	W.I. laminated	300	20/- cwt.	2·7
Rotor pole cores	C.S.	900	18/- cwt.	7·2
Rotor winding	Cu	1030	10*d*. lb.	43·0
Yoke ring	C.I.	1600	10/- cwt.	7·1
				£115·5

In general, an alternator can be sold at a profit for four times the cost of the active material in it, in this case for, say, £460.

CHAPTER V

SYNCHRONOUS MACHINERY IN PARALLEL

When a synchronous machine, such as is described in the last chapter, is run in parallel with other generators, there are one or two problems which present themselves which can be simply solved by means of the flux and ampere turn diagrams already used.

Let us assume that the other machinery is sufficiently large and powerful to maintain constant, or practically constant, voltage on the common bus bars. This means that the stator flux of the machine under consideration is fixed and is not therefore altered by altering the rotor excitation; let this latter be set at the value obtained from the open circuit magnetization curve, to give the bus bar voltage, and let sufficient steam be admitted to the engine driving it to supply the friction and core losses. The alternator will now neither receive nor give power, and the current will, of course, be zero. The magnet poles will keep exactly in the centre of the revolving stator poles.

Now admit more steam to the engine. The speed is fixed by the frequency of the station; the magnet poles will now, however, run round slightly in advance of the stator poles. This is the condition for power to

be given by the alternator to the bus bars. The amount of this power is a function of the angle by which the rotor poles lead over the stator poles, and is affected solely by the steam pressure behind the pistons of the engine.

There is obviously a limit to the possible amount by which the magnet poles can lead over the stator poles ; if this process is pushed too far the alternator will fall out of step.

If, instead of this, the steam were cut off and the alternator made to do external work on the engine or in other ways, the rotor poles would be held back, and whilst still running the same number of revolutions per minute, would lag by a certain angle behind the stator poles. The machine would then be a synchronous motor, and would take power from the bus bars. If more mechanical resistance were offered to the revolution of the motor, the angle between the rotor and stator poles would be increased until as before a limit was reached and the motor fell out of synchronism.

There is therefore for each excitation a certain angle forward and backward from the mean position beyond which the magnet pole must not go. For an engine which has not a uniform turning moment throughout the revolution this angle becomes interesting.

The condition for successful running is that the magnet pole shall not be separated from the stator pole, supposing the latter to be running uniformly, by more than a certain fraction of its distance from the next pole. The first thing to be noticed is that this condition

becomes harder to satisfy the larger the number of poles, and that the slow-running prime movers, requiring therefore the largest number of poles for a given frequency, are the gas engines, which are the most apt to suffer from cyclic irregularity, and that for the highest speeds, where the pole pitch is very large, the turbines are almost perfect in this respect.

The cyclic irregularity of an engine is usually stated by its makers as a percentage variation in speed throughout the revolution, but this, before it can be of use to the electrical designer, has to be translated into maximum error in position of its flywheel expressed in fractions of a pole pitch. This cannot be done without knowing the number of impulses received per minute, as the error in position depends on for how long the incorrect speed continues in the same direction. For example, suppose a 10-inch pole pitch and a peripheral speed of 5000 feet per minute; let us say that the maximum error allowable is $\frac{1}{20}$ of the pole pitch from the mean position, which would permit a total displacement of 1 inch. If the engine were running uniformly only to within 1 in 300 in speed, the maximum error in velocity would be $\frac{1}{300}$ of 500 feet per minute, or 200 inches per minute, which could only be allowed to continue for $\frac{1}{200}$ of a minute to result in 1 inch error; *i.e.* if the engine ran at 100 r.p.m. it must have at least two impulses per revolution to make the time between the impulses $\frac{1}{200}$ minute.

All this time we have not considered the excitation of the alternator. Unlike the case of direct current

generators in parallel, the excitation is powerless to determine which alternator shall take the load, or indeed whether a particular alternator shall run as generator or motor; for if the engine were tending to run faster than synchronism, the machine would generate with a very weak field, or if there was a mechanical resistance to its turning it would run as motor with a strong field.

Considering any group of alternating current machinery, generators or synchronous motors, running in parallel, they jointly require a certain amount of magnetizing force, and this can be supplied by all or any, generator or motor. If one generator or motor be over-excited it will relieve the others of some of their magnetizing work; the medium by which this is transferred being, of course, the phase of the current in respect to the E.M.F.

Take the case of a synchronous motor driving on to a steady load and taking power from constant potential mains, then the stator flux, the speed and the KW. input are all fixed. On the vector diagram (Fig. 13) let OV represent the stator volts and likewise the stator flux to convenient scales. As the machine is acting as a motor, the current will in the main oppose the voltage; let it be represented by OC. The power input is $OV \times OC \times \cos\phi$, which, being fixed, means that C must always be on the line AB. The stator leakage flux OS is, as before, at right angles to the current, and the air space flux is the resultant of this and the stator flux OV, namely VS. Measure along SV a length ST, representing the ampere

turns obtained from the synthesis using the stator, air space, and magnet fluxes as before. The demagnetizing ampere turns, which are proportional to OC, are also at right angles to the current; let SR represent them on the same scale, then TR represents the total rotor excitation. This length TR is the thing we have control of. By adjusting the excitation, OC can be brought into line with OV, when the power factor will become unity and the current for that particular load on

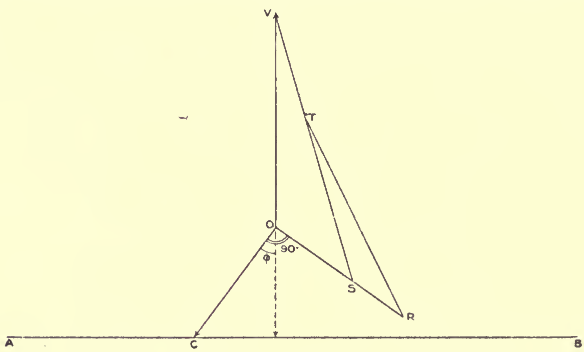

FIG. 13.

the motor is a minimum, as are also the lengths of OS and SR.

If the excitation be reduced from this value the current OC swings to the other side, the power factor becomes less than unity, and OS and SR again increase.

When C is toward A the motor is magnetizing for the rest of the circuit, and from the point of view of the generator supplying it, takes a leading current. When C is toward B the motor is only partly magnetized by its own rotor and partly by the alternating current,

which would then form a lagging or demagnetizing current for its generator. In fact, as ampere turns are taken off the motor's magnets they have to be put on to some other magnets, or the voltage of the system will suffer.

Just the same reasoning applies if the machine, instead of being a motor on constant load, were a generator in parallel with others and driven by an engine with fixed steam admission. The alternator could be made to do more or less of its share of magnetization, *i.e.* give a lagging or leading current, by alteration of its excitation.

CHAPTER VI

COMPOUND WOUND ALTERNATORS

It has been seen that it is, in general, the inherent regulation of an alternator which most seriously limits the output to be obtained from a given size of carcass; the heating limit can usually be overcome by efficient ventilation, and space can generally be found for more copper on both stator and rotor; also, by reason of the variation of voltage caused by changes of current, the full load output has frequently to be fixed below that at which the maximum efficiency occurs.

The direct current generator meets this difficulty by placing an additional winding on the magnets in series with the armature, and it was on this analogy that the first attempts were made to effect a similar result in the alternating current generator.

The problem is, however, in this latter case, complicated by two different difficulties, the first being that the output is in the form of alternating current, and therefore unsuitable as it stands for energizing magnets; and secondly that the voltage drop in an alternator, and therefore the extra magnetization needed, depends, not only on the amount of current, but also on its power factor; in fact, it depends much more on the

power factor of the current than on its actual amount in amperes.

There are, however, some classes of load in which the power factor does not vary much, or, better still, improves as the load on the alternator increases. Such cases can be dealt with by the simple method of rectifying a portion of the main current, usually by a commutator attached to the alternator itself, and by means of additional slip rings, sending this rectified current round a separate winding on the magnets exactly like the direct current analogy. The commutator used to rectify the current is, however, rather liable to give rise to sparking troubles, which can, nevertheless, be eliminated by careful design and adjustment.

The use of small auxiliary transformers enables voltages at different angles to be combined, and the resultant of them, after passing through the rectifying commutator, employed for the purposes of excitation. This resultant voltage can be made to increase either as the current output increases or as the power factor decreases; in a three-phrase circuit, for instance, the current in one phase and the voltage across two phases are at an increasing angle as the power factor decreases, and therefore the resultant will increase as above, and can be used to supply the additional magnetization required for both these causes of the voltage drop.

To overcome the disadvantages inherent to the use of rectifying commutators, and also the complication of two separate windings on the magnets, each with its

own slip-rings, a method has been developed by which the alternating current output is made to increase the voltage of the exciter itself, and thus automatically to increase the excitation.

To attain this end, the armature winding of the exciter is provided with slip rings just as if it were a rotary converter, the number of poles being arranged to give the same frequency as the main alternator. If now these slip rings are fed from a series transformer in the feeder circuit there will be produced in the air space of the exciter a magnetic field which, if the armature were stationary, would revolve just as the field of an induction motor revolves. But as the armature is itself revolving at the same speed in the opposite direction, this field is really stationary in space, exactly like the field produced by the exciter's own magnets; if these latter are capable of adjustment by turning round on their own bearings, the centres of the two sets of poles can be made coincident and aiding each other; let this be so only when the power facter is as low as is likely to occur in practice, for that particular load. If now the power factor improves, the current will reach its maximum earlier in point of time, which means that the resulting pole will be displaced in relation to the field magnet pole of the exciter, and the two no longer being coincident, the result will be a weakening of the air space induction, and therefore, of the exciter voltage.

It is seen that the conditions for automatic voltage regulation are thus fulfilled, for if the current increases

with constant power factor the pole strength increases, the pole remaining fixed, whereas if the power factor decreases with constant current, the pole, whilst remaining constant in strength, is moved round to more nearly coincide with the field pole, and so the effect of the two is increased.

All the methods hitherto described suffer from the defect that they are not instantaneous in their action. To take the last described as an example, although increased magnetizing force is applied to the exciter directly the current in the alternator increases or the power factor decreases, the flux through the exciter is only built up by a process that takes time. When this flux is increased the exciter voltage is indeed immediately increased, but this voltage can only affect the alternator magnet current gradually, which in its turn can only raise the alternator voltage by means of the comparatively slow increase of the alternator flux. On the other side, there is only one process to balance all these, *i.e.* the drop in terminal voltage does not instantaneously follow the increased output, but only through the reduced total excitation lessening the alternator flux.

Processes such as described above must of necessity be slow, because the force producing them is in every instance only just sufficient to give the required result as a steady condition, the exponential term, under such conditions, never really disappearing. This fact is realized by such devices as the Entz booster and the Tyrrell regulator, which are alike in applying forces

many times greater than those finally required, and thus accelerating matters by making the whole process merely the initial stages of a far greater change, which however, is again checked as the required result is attained.

There are other methods of compounding alternators which aim at cutting out all these subsidiary stages, and making the armature reaction itself counteract its own evil effects. One of these methods, due to Mr. Miles Walker, employs rotor poles made up of two parts, magnetically in parallel. The magnet winding is wound on one of these only, which in consequence becomes highly saturated. The effect of the armature reaction is to weaken one pole tip and to strengthen the other. Things are so arranged that the one to be weakened is the highly saturated part, which consequently is not much affected, whilst the other unsaturated pole becomes strengthened and adds to the total flux, and therefore to the voltage of the machine. At unity power factor this can be made to over-compound the alternator, the voltage actually increasing as the current increases, but the effect becomes less as the power factor decreases.

CHAPTER VII

INDUCTION MOTORS—THEORY

In the synchronous machines dealt with in the last chapter the magnetization of the circuit was obtained wholly or in part from a system of direct current magnets. As we have seen, this gives a ready method of controlling the phase relations of the current and the E.M.F.

The power factor, however, of an alternator is a function, not primarily of its own, but of the circuit which it supplies with energy. Induction motors, on the other hand, derive their magnetization from the alternating current generators from which they are driven, and therefore always form for these latter a load having a power factor less than unity, lagging.

It is of the utmost importance, from all points of view, that this magnetization be done in the most efficient way possible—in other words, that the power factor of the induction motor should be as high as possible. For a low power factor not only, as we have seen, affects the voltage regulation of the generators, their heating and efficiency, together with the earning capacity of the cables connecting the two, but also to a still greater degree, the behaviour of the motor itself.

Compare two induction motors with the same input and therefore with approximately the same cost of materials, the one with a maximum power factor of 0·8, the other 0·9. The latter will not only do $12\frac{1}{2}$ per cent. more horse-power, but will have an overload capacity of more than double the former's.

These facts make the predetermination of power factor of preponderating importance in the design of induction machinery, and we shall therefore examine into this question at some length.

Unlike the alternator, the induction motor starts with a certain fixed stator flux depending only on the voltage and frequency of supply, and on the number of turns on the stator winding; as these are all fixed quantities, so also is the stator flux.

Now it is only that portion of this flux which penetrates into the rotor, and is cut by the rotor conductors, which is used in the production of brake horse-power, so that any leakage of lines that occurs in the process must be taken from the available fixed supply, and the problem develops into a study of waste fields.

When the motor is running light, the very small stator currents drawn from the supply mains are only those used to magnetize the circuit and to cause sufficient lines to flow round to produce a counter E.M.F. almost equal to that of supply. Under these conditions the waste field is very small, and most of the stator flux finds its way into the rotor. But as an increasing load is put on, the rotor conductors lag behind

the revolving field, are cut by it, and consequently have current induced in them; these currents tending to oppose the magnetizing currents in the stator, the latter are increased proportionately to their respective turns. All these currents give rise to waste fields, which have ultimately to be supplied from the stator flux.

As the load on the shaft of the motor increases this process continues, until by the increase of the leakage fluxes the portion penetrating into the rotor is no longer sufficient to provide the torque demanded, and the motor falls out of step.

The various leakage fluxes naturally fall under three descriptions: there is the true slot leakage, *i.e.* the lines caused by the magnetizing power of the currents in the slots, and which jump across from the sides of the teeth without entering the air space; there is a somewhat similar leakage flux round the conductors forming the end connections. These are not helped by the existence of teeth, and so have most of their path in air. Their amount depends to some extent on whether the end connections are bound down on to an iron flange, and also on the way in which the end connections are grouped, as already mentioned in considering the analogous case of an alternator.

These two leakage fluxes exist in both stator and rotor separately, but there is a third, which is caused by their joint action on the opposite sides of the air space. If the tooth leakage lines be drawn coming out from the tops of the teeth and bending round, it will

be seen that those from stator and rotor will combine, especially when the tooth of one is opposite the slot of the other, and form a flux which zigzags across the air space, obtaining its magnetization alternately from stator and rotor currents.

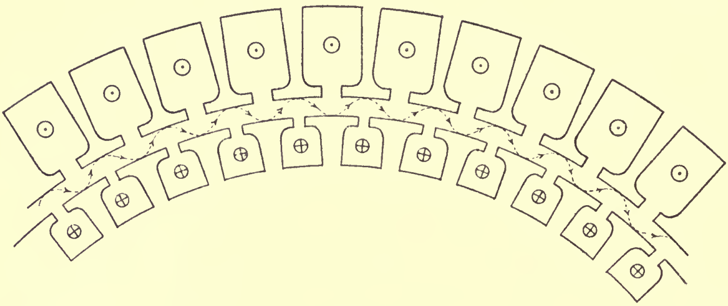

FIG. 14.

In some such way as this various writers have essayed to build up an expression for the total waste field in terms of the stator flux. This fraction—total leakage flux over total stator flux—is usually called σ. Expressions for σ generally contain three terms representing the three sources of leakage, viz. zigzag, slot, and end connections.

Unfortunately, the calculation of waste fields from first principles, although it can be used to give the general form to the expression, is too difficult and uncertain to rely upon solely for the numerical values of the constants deduced, which latter must always chiefly rest on empirical authority. With these remarks we will proceed to show how the three terms of such an expression for σ are arrived at.

In a two-pole induction motor, let—

N be the number of slots per pole, total.

T be the number of turns in series per phase.

δ be the radial clearance between stator and rotor in cms.

τ be the pole pitch, north to south, in cms.

l be the gross length of plates, exclusive of ventilation spaces, in cms.

C be the stator current in R.M.S. amperes.

The area of the air space, allowing, say, 15 per cent. for slot openings, is $0{\cdot}85 \, . \, l \, . \, \tau$ cms²., and its length δ cms. The maximum ampere turns driving the flux are $\frac{\sqrt{2}CT}{2}$. Assuming a sine wave distribution of flux over the surface of the pole, the maximum induction is $\frac{\pi}{2}$ times the average; allowing, say, 20 per cent. extra magnetizing force for the iron parts of the magnetic circuit, the stator flux produced is—

$$\frac{\sqrt{2}CT}{2 \times 0{\cdot}8} \times \frac{0{\cdot}85 l\tau}{\delta} \times \frac{2}{\pi} \times \frac{1}{1{\cdot}2} = \frac{0{\cdot}4CTl\tau}{\delta}$$

For the zigzag leakage the current in each slot magnetizes for that section. The current per slot is $\frac{3TC}{N}$. The area of the path of the lines is $\frac{1}{2} \times \frac{\tau}{N} \times l$, and its length is 2δ.

The flux produced is therefore :—

$$\frac{3\sqrt{2}CT}{0{\cdot}8N} \times \frac{1}{2} \times \frac{\tau}{N} \times \frac{l}{2\delta} = \frac{1{\cdot}3CTl\tau}{N^2\delta}$$

This expressed as a fraction of the stator flux above is—

$$\frac{\mathrm{CT}l\tau}{\delta\mathrm{N}^2} \times \frac{\delta}{\mathrm{CT}l\tau} \times \frac{1\cdot 3}{0\cdot 4} = \text{say } \frac{3}{\mathrm{N}^2}$$

For the slot leakage from the sides of the teeth a figure can be found giving the lines per cm. of slot per ampere in the slot, much as for the alternator already discussed; this figure is in the neighbourhood of 1, which makes the slot leakage flux $3\frac{\sqrt{2}\mathrm{CT}l}{\mathrm{N}}$ or as a fraction of the stator flux—

$$\frac{3\sqrt{2}\mathrm{CT}l}{\mathrm{N}} \times \frac{\delta}{0\cdot 4\mathrm{CT}l\tau} = \text{say } \frac{10\delta}{\mathrm{N}\tau}$$

The end connections have to be treated in much the same way. Let us say that they have half a line per ampere per cm., and that they form a semicircle each side on the pole pitch as diameter. The waste field due to this cause will be then $\sqrt{2}\mathrm{CT} \times \pi\tau \times 0\cdot 5$, and as a fraction of the stator flux, $\frac{5\delta}{l}$.

Gathering together these three terms, we may write

$$\sigma = \frac{3}{\mathrm{N}^2} + \frac{10\delta}{\mathrm{N}\tau} + \frac{5\delta}{l}$$

But, as before stated, the whole rests on an entirely empirical basis, and the constants must be made to fit the experimental results, even if a certain amount of violence is done to theoretical basis of the formula. It is only as the expression succeeds in interpreting the

results of past work that it has any claim to predetermine future results.

To give some idea of how the three terms of the expression work out in practice, we may take a fairly typical case, where—

$$N = 12, \tau = 10, \delta = 0{\cdot}1, \text{ and } l = 20$$

Then
$$\sigma = \frac{3}{144} + \frac{1}{120} + \frac{0{\cdot}5}{20}$$
$$= 0{\cdot}0208 + 0{\cdot}0083 + 0{\cdot}025$$
$$= 0{\cdot}054$$

In the case of motors having squirrel-cage rotors, the last term is usually some 30 per cent. less.

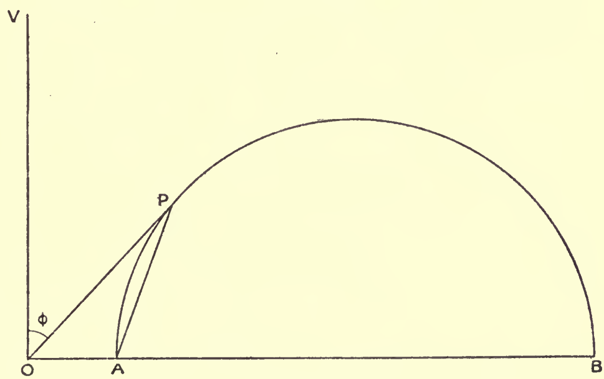

Fig. 15.

Having obtained a value for σ, we can construct the Heyland diagram, Fig. 15, in which OB represents the total stator flux, and OA the leakage flux at no load, AB being therefore the rotor flux and $\frac{OA}{OB}$ being σ. At any other load the leakage flux is, to the same scale, represented by OP and the rotor flux by PB, where

P is any point on the semicircle which is drawn on AB as diameter. As P moves round the semicircle from A to B the leakage flux is seen increasing and the rotor flux decreasing until, as previously stated, the motor has not sufficient rotor flux to maintain the load and consequently falls out of step and stops, in which case the stator flux is all leakage and both are represented by OB.

Exactly the same diagram represents the currents in the motor. OA is the stator current on no load to some suitable scale, any other stator current being represented by OP; this becomes equal to OB when the rotor is standing and short-circuited. PA is proportional to the rotor current, the actual rotor current being obtained by multiplying the length of PA by the ratio—stator turns over rotor turns.

The direction of the voltage vector is OV at right angles to OAB, so that the cosine of the angle VOP is the power factor, and the maximum value this can reach is when OP is a tangent to the semicircle, when it follows from the geometry of the figure that

$$\cos\phi \text{ max.} = \frac{1-\sigma}{1+\sigma} \text{ or } \sigma = \frac{1-\cos\phi \text{ max.}}{1+\cos\phi \text{ max.}}$$

The stator current at no load is, as we have seen, the magnetizing current required to drive the stator flux through the magnetic circuit, and as such is correctly shown at right angles to the voltage; this magnetizing current is always the resultant of the stator and rotor currents. If all the data are known for a proposed motor, the magnetizing current can be

calculated, as also can σ, so that these two being known the Heyland diagram can be constructed and the whole behaviour of the motor predicted in the manner to be shown later.

By making a few assumptions we can now determine about what proportion the magnetizing current should bear to the full-load current. Calling the no-load current Co, it is seen from the diagram that AB is very nearly equal to $\frac{Co}{\sigma}$. The input of the motor is $E \times OP \cos\phi$; the maximum value of $OP \cos\phi$ is $\frac{AB}{2} = \frac{Co}{2\sigma}$.

If the motor is to stand, say, 100 per cent. overload without coming out of step, the full load is half the maximum load. Let us assume the efficiency of the motor at full and maxium load to be 0·9 and 0·7 respectively and the power factor at full load to be 0·9.

The maximum input is, as we have seen, $E \times \frac{Co}{2\sigma}$, the maximum output is 0·7 of this, and the full-load output half of the maximum, or $E \times \frac{0{\cdot}7}{2} \times \frac{Co}{2\sigma}$. With a full load efficiency and power factor both 0·9, the current corresponding to normal full load is $\frac{0{\cdot}7}{2} \times \frac{1}{0{\cdot}81} \times \frac{Co}{2\sigma} =$ say, $\frac{Co}{5\sigma}$.

In the case we were considering, where $\sigma = 0{\cdot}054$, Co is 0·27C, and in practice the no-load current is usually about a quarter of the full-load current.

The current at which the maximum power factor occurs is, by the geometry of the Heyland diagram, equal

to the no-load current divided by $\sqrt{\sigma}$. For this to agree with $C = \frac{Co}{5\sigma}$, σ would have to equal 0·04.

The sort of limits which fix the output of an induction motor are very much the same as affect the other classes of electrical machinery, viz. temperature rise, overload capacity, and efficiency, with power factor thrown in to make it more difficult.

As was the case with alternators, so it is with induction motors, that the specific loading, expressed either as amperes per unit of circumference or ampere turns per unit of diameter, should not exceed certain limits. In the case under consideration the limit is somewhere about 350 to 400 A.T.'s per cm. of diameter, corresponding to 900 to 1000 A.T.'s per inch diameter.

For a given output we have seen that, firstly, the magnetizing current is approximately fixed at one-fourth of the full-load current. The full-load power factor demanded fixes an upper limit to σ which keeps both the number of slots per pole and the length of the motor up, whilst questions of overload capacity and temperature rise both limit the ampere turns per cm. diameter.

CHAPTER VIII

EXAMPLE OF THE DESIGN OF AN INDUCTION MOTOR

To illustrate the preceding theory, we will take the design of a 50-H.P. induction motor to the following specification :—

Three phase, 50 ∼, 500 volts, wound rotor. Speed 750 r.p.m. on no load and not less than 725 r.p.m. on full load. Efficiency not less than 91 per cent. at full load, and corresponding power factor not less than 90 per cent.

Temperature rise not to exceed 40° C. after six hours full load. The motor to take 100 per cent. overload momentarily without falling out of step.

The full-load current per phase, at the above efficiency and power factor, is 53 amperes.

For a full-load power factor of 90, the maximum should not be less than, say, 91, and for this σ equals $\frac{0{\cdot}09}{1{\cdot}91} = 0{\cdot}047$.

The number of poles is eight.

The number of slots per pole per phase should be a whole number, and there is a decided prejudice in favour of having a different number for stator and rotor, which course will be followed here, although facts show

that there is very little against having the same number of slots in stator and rotor where the latter is wound.

Three slots per pole per phase would probably make the attainment of a power factor of 90 per cent. difficult or impossible, so try 4 and 5 for stator and rotor, equal to 12 and 15 per pole respectively. This brings N, the mean of stator and rotor, to 13·5, and the first term of the σ expression to 0·0164, leaving 0·0306 for the other two terms.

A clearance of one millimetre per side between stator and rotor is sufficient, so that a length of 19 cms. would make the third term 0·0263. The middle term would then be satisfactory with a pole pitch τ of anything over 17 cms.

It now becomes a question of adjusting the diameter to obtain a suitable figure for the induction in the air space, which should be somewhere about 5000 lines per cm^2. On the basis of 400 ampere turns per cm. of diameter and a length of 19 cms., the pole pitch of 17 cms., necessitating a diameter of 43·5 cms., would give an air space induction of about 6800, allowing 15 per cent. for slot openings. On the above assumptions the air space induction varies inversely as the square of the diameter, so for B 5000, the diameter would be about 51 cms. We have yet to see if this fits the possible number of conductors per slot; the total turns corresponding to 51 cms. diameter at 400 A.T.'s per cm. are 384, which divided by 96, the number of stator slots, makes 8 conductors per slot, which number will be satisfactory. The turns per phase will be 128; if the

diameter is made 50 cms. the A.T.'s per cm. at 53 amperes will be 407.

The full-load stator flux is

$$\frac{500}{\sqrt{3}} \times \frac{\sqrt{2} \times 10^8}{2\pi \times 50 \times 128} = 1{\cdot}02 \times 10^6$$

This contains small allowances both for the distributed nature of the winding and for the volts lost in its resistance, which two, in a motor of this size, about balance each other.

The full expression for σ is now

$$\begin{aligned} &\frac{3}{13{\cdot}5^2} + \frac{10 \times 0{\cdot}1}{13{\cdot}5 \times 19{\cdot}5} + \frac{5 \times 0{\cdot}1}{19} \\ &= 0{\cdot}0164 + 0{\cdot}0038 + 0{\cdot}0263 \\ &= 0{\cdot}0465 \end{aligned}$$

The rotor flux $= 1{\cdot}02 \times (1 - \sigma) = 0{\cdot}97 \times 10^6$.

Take the air space flux as halfway between these, say, 1×10^6.

The 19 cms. of plates should be broken up into four sections with 1·5 cm. ventilation spaces between each, which makes the length between end plates 23·5 cms. Taking plates 0·015″ thick, and varnishing both sides to 0·017″ total thickness, the net length of iron is 16·8 cms.

For the maximum induction in the teeth not to exceed 17,000, an area of 94 cms^2. is required; there are 12 teeth per pole, each tooth therefore must be 0·47 cm. The minimum pitch of the teeth is 1·64 cms., leaving 1·17 cms., say 11 mm., for the slot width. Winding this with round wire two abreast, lining the slot with a micanite tube 1 mm. thick, and covering the wire with a

cotton braid to 0·5 mm. on the diameter and allowing 1 mm. margin, leaves 3·5 mm. for the diameter of each wire, or 9·6 mm². area. Two of these in parallel will carry 53 amperes at a density of 2·75 amperes per mm²., which is quite suitable.

The average length of one turn made up of two straight pieces 23·5 cms. long each, and two semicircles on the pole pitch of 21 cms., is 113 cms., which makes the resistance of the 128 turns of two wires in parallel 0·13 ohm at 15° C., or 0·15 ohm at 60° C. The loss in the three phases warm will be 1·26 KW., which is about 3 per cent. of the input.

There will be 8 wires deep in the slot, which, allowing 2·5 mm. for the roof and 1·5 mm. for margin, makes 38 mm. depth of slot. Leave 2 mm. opening at the top of the slot.

The double depth of plate behind the slot for, say, 6000 lines per cm². would be 10 cms., making the outside diameter of the stator plate 67·6 cms., say, 68 cms.

In the rotor, for a maximum induction of 17,000 in the teeth, an area of 89 cms². is required. There are 15 teeth per pole, so that each tooth must be 3·6 mm. Assuming a depth of slot of 25 mm., the pitch of slots minimum would be 11·7, which leaves 8·1, say 8 mm., for the slot.

The simplest of all windings is two bars per slot, which would give 40 turns per phase, in which case the volts between slip rings would be $500 \times \frac{40}{128} = 156$, which is quite convenient.

For a first approximation the rotor current may be taken as equal to the inphase component of the stator current multiplied by the ratio of the turns, in this case $53 \times 0{\cdot}9 \times \frac{128}{40} = 153$ amperes. Copper to carry this at 3 amperes per mm^2. would be 51 mm^2. The 8 mm. slot will take a 5 mm. wide bar by 10 mm. deep, say. Two of these will go into a 28 mm. deep slot. So rotor slots are $120 - 28 \times 8$, with 2 mm. opening.

The average length of one turn of the rotor winding is made up of two pieces 23·5 cms. long each and two end connections each, say, twice the pole pitch of 18·5 cms., making 121 cms. total. The resistance of 40 turns is therefore 0·0165 ohm cold and 0·019 ohm warm. The total loss at 153 amperes is hence 1·34 KW., or 3·4 per cent. of the input to the rotor, which will make the full-load speed very nearly 725 r.p.m.

The internal diameter of the rotor plate is settled, in this case, not so much from electrical as mechanical reasons, which call for a depth of not less than say 4 cms. a side, which makes the hole in the rotor plate 36 cms. in diameter, the corresponding induction being 7000 lines per cm^2.

We can now proceed to the synthesis of the magnetizing force required. The areas of the teeth will be taken, as for the alternator already described, one-fifth of the way from the smaller end. The air space area will be the mean of the areas of the roofs of the teeth in stator and rotor plus 10 per cent. for spread.

For the circuits in teeth and cores the net length of

iron will be taken 16·8 cms., but for the air space the length of the assembled plates—19 cms.—is used. The length of the path in the plates at the back of the teeth is taken as half the pole pitch at the mean diameter plus the depth of the plate.

The maximum induction in teeth and air space is taken as $\frac{\pi}{2}$ times the average.

With these explanations the synthesis can be tabulated as follows :—

	Length of circuit cms.	Area of circuit cms².	Flux $\times 10^6$.	B lines per cm². max.	H per cm.	$H \times l$ C.G.S. per 2 poles.
Stator core $\times$ 2 ...	17·5	174	1·02	5,850	1·5	26
Stator teeth $\frac{1}{3}$ ...	7·6	119	1·02	13,500	7·5	57
Air space	0·2	353	1·0	4,450	4,450	890
Rotor teeth $\frac{1}{3}$ ...	5·6	98	0·97	15,500	15·0	84
Rotor core $\times$ 2 ...	12·0	138	0·97	7,000	2·0	24
					Total C.G.S. per 2 poles =	1081
					Ampere turns per pole =	432

Now, this magnetization of 432 A.T.'s is derived from all the three phases. For the alternator it was seen that the demagnetizing effect of these was $\frac{\sqrt{2}}{2} \times$ R.M.S. current per phase $\times$ total turns per pole on all phases. By the same reasoning the magnetizing current per phase of this motor is $\frac{432 \times 2 \times 8}{128 \times \sqrt{2} \times 3}$ $= 12{\cdot}8$ amperes.

The value of this no-load current from the approximate expression $Co = C \times 5 \times \sigma$ would work out in

this case to $53 \times 5 \times 0{\cdot}0465 = 12{\cdot}3$ amperes, which shows a very fair agreement.

The static current, OB on the Heyland Diagram, is $\dfrac{12{\cdot}8}{0{\cdot}0465} = 275$ amperes. We now have all the data necessary to construct the diagram. Nothing further, however, can be done till the details of efficiency are available.

For the core loss take, as for the alternator, the weight of plates before the slots are cut away, in this case 480 lbs. at an induction of 5850, which is proportional to 1·55 watts per pound on the total loss curve. This makes 0·75 KW., or allowing for windage and friction, say 1 KW.

The resistance of the three phases of the stator winding warm is 0·45 ohm, and that of the rotor 0·057 ohm.

If the diagram be drawn on some good squared paper, and a scale of amperes be made on the vertical edge, certain selected stator currents can be set off on dividers from the point O, and pricked off where the end of their vector would touch the circle. The vertical heights of these points can be read off on the same scale and give the inphase component of the stator current; the power factor is obtained by dividing the inphase by the total current (Fig. 16).

The rotor currents are proportional to the length PA (Fig. 15). If the rotor resistance be increased by the square of the ratio of turns in stator and rotor respectively, and this new resistance be multiplied by

the square of this length, to the same scale as for the stator currents, the rotor copper loss is obtained. This new rotor resistance would be, in this case, $0{\cdot}057 \times (\frac{128}{40})^2 = 0{\cdot}58$ ohm.

The square of the stator current by 0·45 gives the stator copper loss; adding the sum of these to the core windage and friction loss gives the total loss. The

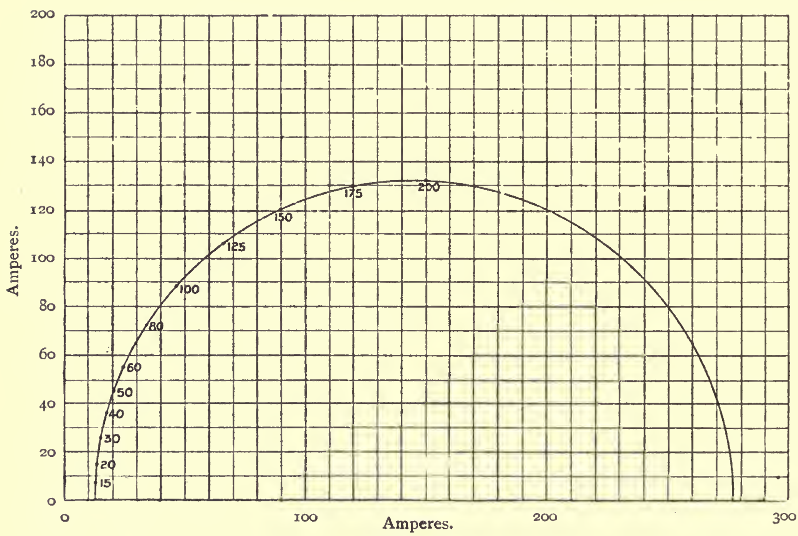

FIG. 16.

input is $\sqrt{3} \times 500 \times$ inphase component of stator current. The output is this minus the total loss, and the brake horse-power is the output divided by 0·746.

The slip is the rotor copper loss divided by this loss plus the motor output. The efficiency of the motor output over input for each current, can also be written down.

Stator current.	In phase component.	Power factor cos φ.	Stator C²R KW.	Proportional rotor current.	Rotor C²R KW.	Total losses KW.	Input KW.	Output KW.	B.H.P.	Slip per cent.	Efficiency per cent.
15	7·0	0·47	0·1	7·0	0·03	1·13	6·08	4·95	6·6	0·6	81·5
20	14·0	0·7	0·18	14·0	0·11	1·29	12·16	10·87	14·6	1·0	89·4
30	25·5	0·85	0·4	25·5	0·38	1·78	22·0	20·2	27·0	1·8	91·9
40	35·5	0·885	0·72	35·5	0·73	2·45	30·7	28·2	37·9	2·5	92·0
50	45·0	0·9	1·12	45·5	1·2	3·32	39·0	35·7	47·9	3·3	91·5
60	54·5	0·91	1·62	56·0	1·82	4·44	47·4	42·9	57·4	4·0	90·6
80	72·5	0·905	2·87	76·0	3·34	7·21	63·0	55·8	74·7	5·7	88·5
100	89·0	0·89	4·5	95·0	5·22	10·7	77·0	66·3	88·8	7·3	86·1
125	106·0	0·85	7·0	119·0	8·2	16·2	92·0	75·8	102·0	9·8	82·4
150	120·0	0·8	10·2	143·0	11·9	23·1	104·0	80·9	108·0	12·9	78·0
175	129·0	0·74	13·8	168·0	16·4	31·2	112·0	80·8	108·0	16·9	72·0
200	132·0	0·66	18·0	190·0	20·9	39·9	114·0	74·1	100·0	22·0	65·0

These results are plotted, not against stator current, but against B.H.P. The curves will then show the

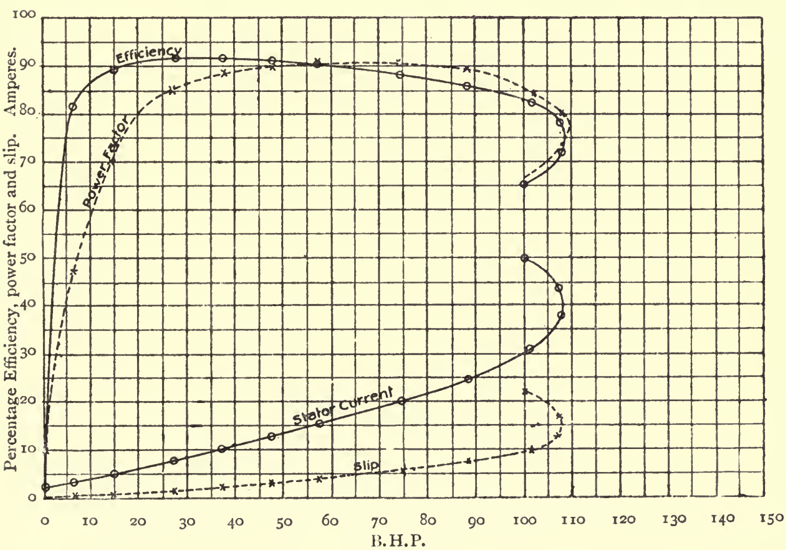

Fig. 17.

efficiency, power factor, slip and stator current for any particular H.P.

From these curves it is seen that for 50 B.H.P. the stator current is 52 amperes, the efficiency is 91·3, and the power factor 90·3 per cent. The full-load slip is 3·4 per cent., which makes the full-load speed 725 r.p.m.

The curves begin to bend back at 109 H.P., and are commencing to show instability soon after 100 H.P.

The power factor running light is got from the fact that the input is about 1·1 KW.—allowing 0·1 KW. for stator and rotor C^2R loss—whilst the imput in K.V.A. is $\frac{\sqrt{3} \times 500 \times 12{\cdot}8}{1000} = 11$. The power factor is therefore about 10 per cent.

The maximum power factor, from the diagram, is 91 per cent., and occurs at a stator current of 60 amperes.

The efficiency is a maximum at about three-quarter load, and is over 90 per cent. from about 15 to 65 H.P.

Weights and Costs of Active Material.

	Material.	Weight in lbs.	Rate.	Cost.
				£
Stator plates	M.S.	370	30/- cwt.	4·95
Rotor plates	M.S.	190	30/- cwt.	2·55
Stator winding	Cu	160	1/- lb.	8·0
Rotor winding	Cu	140	1/- lb.	7·0
			Total cost of active material	£22·5

As for the alternator, this motor would probably be sold at a profit for four times this, or £90.

CHAPTER IX

STATIC TRANSFORMERS

After the study of generators and motors, it is quite in place to look to transformers.

The two oldest forms of static transformers are the ring of iron with primary and secondary windings wound round it, and the induction coil with a single straight core with both windings upon it. The first has given rise to the core type of transformer, but now has its parts rectangular; and the latter to the shell type, so called from the iron which completes the magnetic circuit enclosing the windings.

Consider a simple transformer of, say, the core type, with two windings of T_1 and T_2 turns respectively, having resistances R_1 and R_2 ohms. Call the ratio of turns, T_1 over $T_2 - \rho$.

If, the secondary winding being on open circuit, an alternating voltage is impressed on the primary, current will flow in increasing strength until its magnetizing force is sufficient to drive a flux through the iron core, of such a magnitude that the voltage induced thereby in the T_1 turns is equal to the impressed voltage less that used up in the resistance—R_1—of the windings.

This current, in comparison with the full-load current, will usually be very small indeed.

A voltage corresponding to the turns and the flux threading it will also be induced in the secondary coil.

Any current taken from this will be a demagnetizing current, and the primary coil will therefore take an increase of current in the ratio of the turns T_2 to T_1, so that the algebraic sum of the two ampere turns will always be that needed to magnetize the circuit.

On open circuit, the ratio of the secondary voltage to the impressed voltage will be that of the turns T_2 to T_1, but on current being taken from the secondary its terminal voltage will fall, for three reasons : firstly, due to the pressure lost in sending its own current through the resistance of its own windings ; secondly, due to the flux through it having been reduced owing to the corresponding resistance drop on the primary winding ; and, thirdly, due to the fact that both primary and secondary currents set up leakage fields which do not thread the others' coils.

In order to be able to represent the effect of these leakage fields on the same diagram as terminal voltages and volts lost in resistance, it is convenient to translate them into voltages too, remembering that really the leakage fluxes combine with the working fluxes, forming one resultant flux which produces one voltage only in each coil.

To represent both primary and secondary effects on the same diagram one must be brought to terms of the other. Let A_1 and A_2 be the primary and secondary currents

respectively. The current A_1 in the resistance R_1 causes a drop $\frac{R_1A_1}{\rho}$ at the secondary terminals, which adds to the secondary's own resistance drop of R_2A_2.

As the magnetizing current is so small in comparison with the load currents, we may write $A_1 = \frac{A_2}{\rho}$; so that the total drop on the secondary side due to the resistances of both windings is $e_r = A_2\left(R_2 + \frac{R_1}{\rho^2}\right)$; this is in phase with the current.

The reactance voltage drops due to the leakage fields are also proportional to the current, but at right angles to it. The amount of the waste field is as usual very difficult to calculate, as the leakage paths are quite undefined. The total drops due to this cause can, however, readily be measured in terms of the secondary voltage by short-circuiting the primary winding and supplying the secondary winding with sufficient voltage to cause full-load currents to circulate in both. This applied voltage is the resultant of the resistance and reactance voltages at right angles; the former is, of course, easily calculated from the measured resistances, and hence the reactance drop is known.

In a new transformer the result can be predicted from the data obtained from somewhat similar ones on test.

On power factors of unity, or less than unity, lagging, both these causes reduce the secondary voltage.

Let, in Fig. 18, E_2 represent the secondary terminal

voltage. Draw A_2 to represent the direction of the secondary current at an angle ϕ to E_2, where $\cos\phi$ is the power factor of the circuit supplied by the transformer. In the same straight line as A_2 draw e_r to represent the combined primary and secondary resistance drop, to the same scale as E_2. This is in phase with the current. At right angles to this draw e_s, to represent the combined reactance drop. The vector

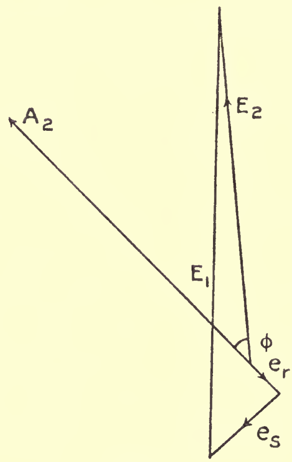

FIG. 18.

joining the end of this with the end of E_2 is proportional to the primary terminal voltage and equal to it if multiplied by ρ.

If e_r and e_s are small compared with E_1 and E_2, then $E_1 - E_2 = e_r \cos\phi + e_s \sin\phi$; that is, the total drop of the secondary voltage from all causes is $e_r \cos\phi + e_s \sin\phi$. This is seen, by the geometry of the figure, to be a maximum when the power factor of the circuit is such that $\tan\phi = \frac{e_s}{e_r}$.

Before leaving this diagram it is interesting to note what happens if the power factor is less than unity but on the leading side of E_2. In this case it is seen that, especially if the magnetic leakage is fairly high, the secondary voltage may be increased instead of diminished as the load increases, and still more so if the current tends to lead more on the pressure as the former increases.

This fact is made use of in the operation of rotary converters, which by nature of the odd value of the alternating voltage required, if for no other reason, are practically always fed through transformers. If it is remembered that a rotary is essentially a synchronous motor, and the paragraphs at the end of Chapter V. be read in that light, it is seen that the provision of a compound winding on the magnets of a rotary converter carrying the main direct current provides an increasing excitation, and therefore a power factor tending from lagging to leading as the load increases. This enables the transformer feeding it to raise its secondary voltage although itself fed from constant potential mains. So that, although the rotary converter operates with a fixed conversion ratio of DC to AC volts, the net result is that the addition of series turns on its magnets raises the voltage on the direct current side with increasing load, exactly like any other over-compound-wound D.C. generator, though really from a very different cause. If necessary the transformers for use with rotaries are made with specially large magnetic leakage in order to effect this end.

The voltage regulation of transformers may be made as close as desired. The resistance drop is a question simply of quantity of copper used, and the reactance drop one of sufficiently interleaving the primary and secondary windings so that the lines made by the one are bound to cut the other also. As both these processes, however, cost money, and are increasingly expensive the further the result is pushed, it is worth while to consider if there are no other corresponding disadvantages.

One other disadvantage, besides the cost, to very close voltage regulation is the difficulty, when running such transformers in parallel, of ensuring that the load divides equally between them. Take the case of two transformers, one having a 9 and the other a 10 per cent. drop; if these are in parallel it is obvious that they must have the same secondary voltage and therefore the same drop, say $9\frac{1}{2}$ per cent., when one will be 5 per cent. under- and the other 5 per cent. over-loaded, which is not of much consequence. But now suppose that the regulation of the two is 2 and 3 per cent. respectively, and say $2\frac{1}{2}$ per cent. when in parallel, one will have 50 per cent. more load than the other, the one being 17 per cent. under- and the other 25 per cent. over-loaded.

The design of transformers is rendered more than usually difficult on account of the apparently unlimited choice which is offered by varying the relative proportions of the iron and copper used. For instance, a 100 V. 50 $\sim$ transformer might have one turn of copper

and a flux of 45 million lines, or a million turns and 45 lines of force. Experience has shown, however, that there exists in well-designed transformers a fairly definite ratio between the flux and the ampere turns, though the value of this ratio naturally depends somewhat on the size and type.

There is then the further choice of the lines per square centimetre in the iron, and the amperes per square centimetre in the copper; the values for these are largely dictated by the efficiency aimed at and by the methods employed to carry off the heat generated; for, whilst in small apparatus, natural cooling may be sufficient to carry off the heat corresponding to quite a moderate efficiency, yet the output increases so much faster than the linear dimensions that in large units, even where quite extraordinarily high efficiencies are obtained, some artificial method of cooling is called for to prevent an altogether abnormal rise of temperature.

This artificial cooling may take the form of a blast of air forced through and round the transformer by an auxiliary fan, or again the whole apparatus may be immersed in oil, which itself may be cooled either naturally or artificially. The former method is cleaner and in some ways more direct, inspection is easier and the heat generated can readily be led out of the building or transformer chamber.

The advantages of oil cooling are that the air circulation is dependent on running machinery, which may fail; the air may be damp or dust-laden. Of the

two, the fire risk with air is greater than with oil cooling. In very high-tension apparatus static discharges may occur in air which combine the nitrogen and oxygen of the atmosphere, forming nitric acid, which deteriorates the insulation and corrodes the copper. Owing to the larger specific heat of oil the overload capacity is greater than with air cooling, and oil is a very good insulator by itself and is self-healing in case of a discharge taking place.

The material used for the electrical circuits is always copper having a fairly constant quality, but the magnetic circuits may be made of different classes of iron or of various alloys of iron containing small proportions of other ingredients. The correct proportions of iron and copper to use for any transformer will vary with the relative cost of the two metals.

Let Pc be the price of copper per cubic inch
Pi be the price of iron per cubic inch
l be the length of the core in inches
d be the diameter of the core in inches
t be the depth of copper a side in inches
Δ be the amperes per square inch
and B be the lines per square centimetre ;

Then, neglecting the space factors for both iron and copper, which, for circular coils at any rate, are not far different, the volume of the iron is $\frac{\pi}{4}d^2l$, and that of the copper $\pi(d + t)lt$, and the total cost of the two will be these expressions multiplied by Pi and Pc respectively.

The volts in a coil are equal to the flux $\times \frac{2\pi\sim}{\sqrt{2}} \times 10^{-8}$ $\times$ turns in the coil. The flux is $\frac{\pi}{4}d^2\mathrm{B} \times 6{\cdot}45$. The output W = volts $\times$ amperes. The ampere turns are $lt\Delta$ and the amperes this divided by the turns, therefore $\mathrm{W} = d^2\mathrm{B}\sim \times lt\Delta \times 22{\cdot}5 \times 10^{-8}$.

Putting this expression into the one for the total cost, we have

$$\text{Total cost} = \frac{\mathrm{W}}{\mathrm{B}\Delta\sim 7{\cdot}2 \times 10^{-8}}\left\{\frac{\mathrm{Pi}}{4t} + \mathrm{Pc}\left(\frac{d+t}{d^2}\right)\right\}$$

which is a minimum when

$$\frac{t}{d} = \frac{1}{2}\sqrt{\frac{\mathrm{Pi}}{\mathrm{Pc}}}$$

This gives the best relation between the depth of copper and the diameter of iron core when the ratio of the costs of iron and copper is known.

For iron plates at 20 shillings a cwt. and copper wire at a shilling a lb. and densities 7·8 and 8·9 respectively, Pc = 6·4 Pi, and the best depth is when $t = \frac{d}{5}$. If, however, we use "stalloy" at twice the price of iron, the minimum cost occurs when $t = \frac{d}{3{\cdot}6}$.

Taking the first value, *i.e.* that the depth of the copper is one-fifth the diameter of the core, and making a few assumptions such as that the length of the core is twice its diameter and that B = 7000 lines per cm^2. and Δ = 1000 amperes per in^2., the value of the ratio—flux to ampere turns—mentioned

before works out to about 180 to 1, which is actually very near the figure met with in practice; the ampere turns being those due to one of the two windings, not both.

The expression for the total cost shows also that this is proportional to the output, but inversely proportional to the induction, the density, and the frequency.

CHAPTER X

EXAMPLE OF THE DESIGN OF A TRANSFORMER

WITH the help of the theory discussed in the last chapter we will now design a three-phase 350 KW. transformer of the three circular core type with common yoke. Primary voltage 2200, secondary 415 volts, 50~, to work on a power factor of 0·85.

The secondary full-load current corresponding to 412 K.V.A. is 573 amperes, and at 98 per cent. efficiency the primary current is 110 amperes, both star connected.

Taking the ratio of flux to ampere turns as 180 to 1, and calling the secondary turns T_2, then

$$\frac{415}{\sqrt{3}} \times \frac{\sqrt{2} \times 10^8}{2\pi \times 50} \times \frac{1}{T_2} = 180 \times 573 \times T_2$$

and $T_2 = 32·3$, say 32 turns per phase in 4 coils of 8 turns each.

The flux will be $3·4 \times 10^6$ lines in each core. The area for this at $B = 7000$ is 75 ins². using plates 0·013″ thick and varnished to 0·015″, the gross area is 86 ins². This may be made up of two blocks 11″ × 3″ and two blocks $5\frac{1}{2}$″ × 2″, which, with half an inch ventilation spaces between each, just fit into a circle of $12\frac{3}{4}$″ diameter and give 88 ins²., the net area of iron being 77 ins². and the induction 6850 lines per cm².

The low-tension winding at 1000 amperes per in^2. requires 0·573 sq. in.; wind this with a number of fairly small square conductors in parallel, say six, each $\frac{5}{16}''$ square, which gives 0·585 in^2. and 980 amperes per in^2. Cover it to say 0·335″ with double cotton.

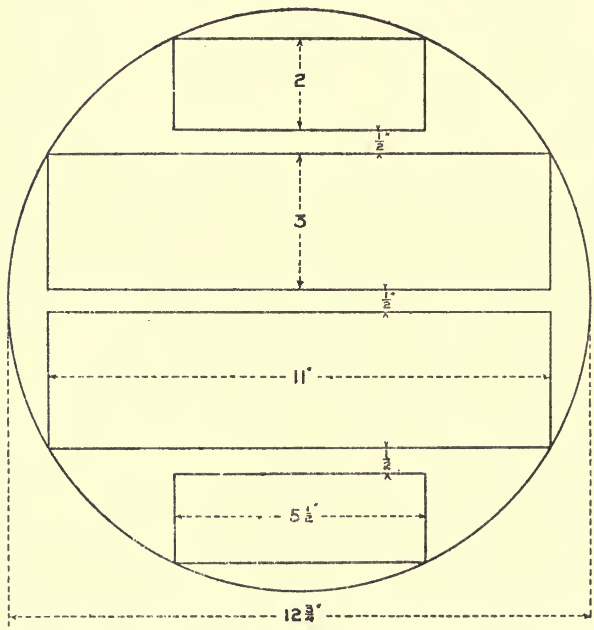

FIG. 19.

Eight turns of this combined conductor would occupy a space 2″ × 2¾″ deep. Allowing ½″ from iron to copper, the inside turn would have a diameter of 13·75″ and the mean diameter of the coil would be 16·5″, making the mean turn 52″. The resistance of 32 such turns would be 0·0019 ohm per phase, and the total weight on three phases 936 lbs.

In fixing the number of primary turns, allow for 420 secondary volts, or 5 volts drop ; the high tension turns are then $32 \times \frac{2200}{420} = 168$. The density should be rather lower here owing to the additional insulation. Two conductors $\frac{1}{4}''$ square in parallel would give an area of 0·125 in². and a density of 880 amperes per in². Cover the conductor to 0·275″ and wind nine layers deep, or $2\frac{1}{2}''$. The three coils in between the low-tension coils can then have 10 conductors side by side, which will take up 2·75″ in width, leaving two coils at the two ends each of four conductors wide, or 1·1″.

The resistance of the 168 turns is 0·0465 ohm per phase, and the total weight 1048 lbs.

Allowing 1 in. between the coils and at each end, the length of the windings is 28·45″, so make the iron core 30″ long.

The distance between centres of the three cores is 20·25″, made up of 12·75″ for the iron, 5·5″ for the coils, and 2″ in clearance space. The total length of the yoke is $2 \times 20{\cdot}25'' + 11'' = 51{\cdot}5''$. The area of the yoke is the same as that of the core, and is similarly arranged.

The total weight of iron is 4150 lbs., the maximum induction 6850 lines per cm². In transformer iron, partly on account of its use in rectangular sheets without teeth, and partly that it need not be subjected to so much ill treatment in manufacture as are core plates for alternators or motors, the loss per pound at similar inductions is much less. In the present case this should not exceed 0·7 watt per pound, or say 3 KW. total.

The copper losses warm are H.T. 1·9 KW. and L.T. 2·1 KW., making a total loss at full load of 7 KW. in an input of 357, or a full-load efficiency at 0·85 power factor of just over 98 per cent. At unity power factor the total loss at 350 KW.'s is reduced to 5·9 KW., and the efficiency works out to 98·3 per cent.

The efficiencies at different loads are shown in the following columns:—

	$\frac{1}{4}$	$\frac{1}{2}$	$\frac{3}{4}$	full	$1\frac{1}{4}$	$1\frac{1}{2}$ load.
Power factor 0·85						
Iron loss	3·0	3·0	3·0	3·0	3·0	3·0
Copper loss	0·25	1·0	2·25	4·0	6·25	9·0
Total loss	3·25	4·0	5·25	7·0	9·25	12·0
Output	87·5	175·0	262·5	350·0	437·5	525·0
Input	90·75	179·0	267·75	357·0	446·75	537·0
Efficiency, per cent.	96·4	97·8	98·0	98·0	97·9	97·8
Power factor unity						
Copper loss	0·18	0·72	1·62	2·9	4·53	6·53
Total loss	3·18	3·75	4·62	5·9	7·53	9·53
Input	90·68	178·72	267·12	355·9	445·03	534·53
Efficiency, per cent.	96·5	97·9	98·3	98·3	98·3	98·2

The cost of active material is: for plates, 4150 lbs. at 20*s.* per cwt., £37; for copper, 2000 lbs. at 1*s.* per lb., £100. Total cost of active material, £137.

The magnetizing current is calculated on the assumption that each phase magnetizes for its own core and the yoke halfway to the next, 30″ and 20″ respectively in length. The joints at each end of the core are taken as equivalent to 0·1 mm. of air.

$$\begin{aligned} H \times l \text{ for air} &= 6850 \times 0{\cdot}02 = 137 \\ \text{,, for iron} &= 2 \times 127 \quad = \underline{254} \\ &\text{Total} \qquad 391 \end{aligned}$$

The magnetizing current is therefore—

$$\frac{391 \times 0{\cdot}8}{168 \times \sqrt{2}} = 1{\cdot}3 \text{ R.M.S. amperes per phase.}$$

For purposes of the calculation of voltage regulation, it is assumed that previous experience with similar transformers would lead one to expect a reactance drop of 3 per cent. The resistance drop in the secondary when warm is $0{\cdot}0019 \times 1{\cdot}15 \times 573 = 1{\cdot}25$ volts, which is 0·52 per cent. in the star voltage of 240. In the primary the corresponding figure is $0{\cdot}065 \times 1{\cdot}15 \times$

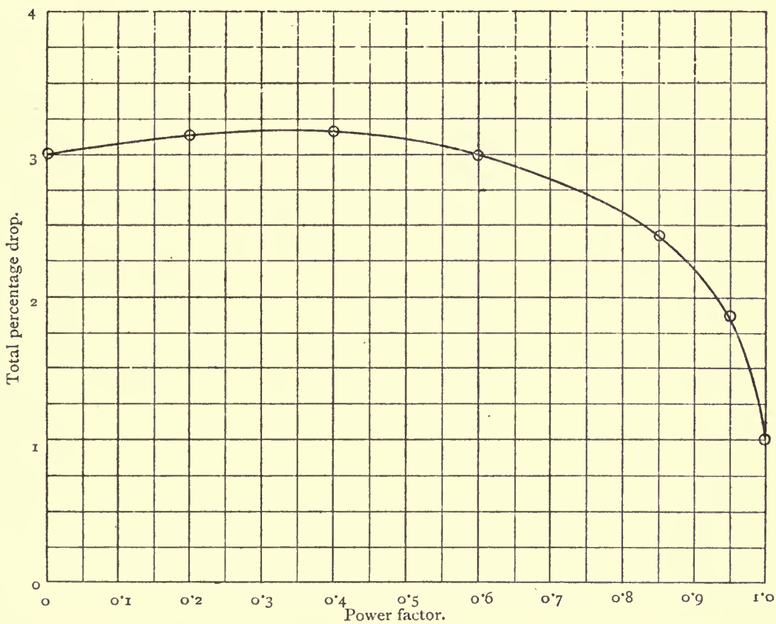

FIG. 20.

$110 = 5{\cdot}9$ volts, or 0·47 per cent. The total resistance drop is therefore, say, 1 per cent.

The total voltage drop from both causes is then $1 \cos \phi + 3 \sin \phi$, where $\cos \phi$ is the power factor of the circuit fed from the secondary. The power factor at which this drop is a maximum is when $\tan \phi = 3$ or $\cos \phi = 0{\cdot}32$, when the drop is 3·16 per cent.

The following table gives the total drop for other values of the power factor :—

Cos ϕ.	ϕ in degrees.	Sin $\phi \times 3$.	Total percentage drop.
1·0	0·0	0·0	1·0
0·95	18·2	0·93	1·88
0·85	31·8	1·58	2·43
0·6	53·1	2·4	3·0
0·4	66·4	2·75	3·15
0·2	78·5	2·94	3·14
0·0	90·0	3·0	3·0

CHAPTER XI

TRANSMISSION LINES

There follows naturally from generators, motors and transformers the question of transmission of electrical energy.

Firstly comes the question as to what system of generating electricity is best adapted for its transmission. A simple comparison can be made of the various systems, on the basis of equal power transmitted for a given distance with a given loss, the pressure at the receiving end being kept the same for all.

For the sake of example, take 100 KW. delivered one mile away with a 10 per cent. loss, the pressure at the delivery end to be 200 volts.

Firstly, on the direct-current two-wire, or single-phase two-wire systems, the current would be 500 amperes. The loss in each line is 5 KW., which requires an area of 2·1 ins^2. of copper and a total weight of 38 tons. The density would be 240 amperes per in^2.

Secondly, direct-current or single-phase three wires with the middle wire 10 per cent. of each outer, but carrying no current. The current in the outers is 250 amperes, the loss in each is as before, 5 KW., which makes the

area of each 0·525 in². with a density of 480 amperes per in². The total weight of copper is 10 tons.

Thirdly, two-phase four wires, which gives the same total weight as for a single-phase, 38 tons.

Fourthly, two-phase three-wires. The current in each outer is 250 amperes and in the middle wire 354. The density is the same in all these, *i.e.* 280 amperes per in². The area of each outer is 0·895 in². and of the middle 1·26 ins². The total weight is 27·6 tons.

Fifthly, three-phase mesh, with 200 volts between each of the three wires. The current in each wire is 288 amperes, the area 1·05 ins²., the density 274 amperes per in²., and the total weight 28·8 tons.

Sixthly, three-phase star, with 200 volts between each wire and the star point. The middle wire to be 10 per cent. of each of the outers, but carrying no current. The total weight of this arrangement is 9·8 tons.

Seventhly, three-phase star, but transforming down to 200 volts at the receiving end. The voltage to be such that the 10 KW. loss is combined with a density of 1000 amperes per in². At this density the drop is 42 volts per mile in each wire, so that the receiving voltage must be 420 star volts, or 730 volts between lines, and 803 volts at the generator end. The current per line is 79 amperes, and the section of each wire 0·079 in². The weight of the three wires (the transformers supply the middle wire) would be 2·15 tons.

Below is a summary of these results :—

1 MILE TRANSMISSION.

100 KW.'s delivered at 200 volts with 10 KW. loss.

System.	Δ amperes per cm².	Total weight in tons.	Per cent. of D.C.
1. D.C. or single phase	240	38·0	100·0
2. D.C. 3 wires, ...	480	10·0	27·0
3. 2-phase, 4 wires	240	38·0	100·0
4. 2-phase, 3 wires	280	27·6	73·0
5. 3-phase, mesh	274	28·5	75·0
6. 3-phase, star	480	9·8	26·0
7. 3-phase, star, with transformers	1000	2·15	5·7

The last case introduces the question of the cheapest voltage to transmit at, because, if the cables be covered, the increased cost of insulation may more than balance the reduced cost of copper.

To obtain this cheapest voltage, certain assumptions have to be made. Few manufacturers will guarantee their cables if worked at more than 1000 amperes per in². on account of temperature ; this is not a very scientific basis, but it is worth while to see what results it will lead to. Another basis of comparison would be equal efficiencies, which can be expressed as equal percentage pressure drop per mile.

In general, manufacturers' catalogues have to be re-arranged in order that the cheapest voltage at which to transmit a given load, at either constant density or constant efficiency may be apparent.

For example, let us assume that we have prices for three-core lead-covered and armoured cables for three voltages and for three sizes at each voltage, as under :—

Cables of 0·01 in². area per core insulated for 1000,

6000, and 10,000 volts between cores and to the sheath, £215, £310 and £425 per mile respectively; for 0·05 in². per core for the same voltages, £450, £550 and £700 per mile; and for 0·1 in²., £720, £825 and £1000 per mile.

Plot these on the same sheet and to the same horizontal scale of £'s per mile, one vertical scale being volts and the other square inches area per core. From the

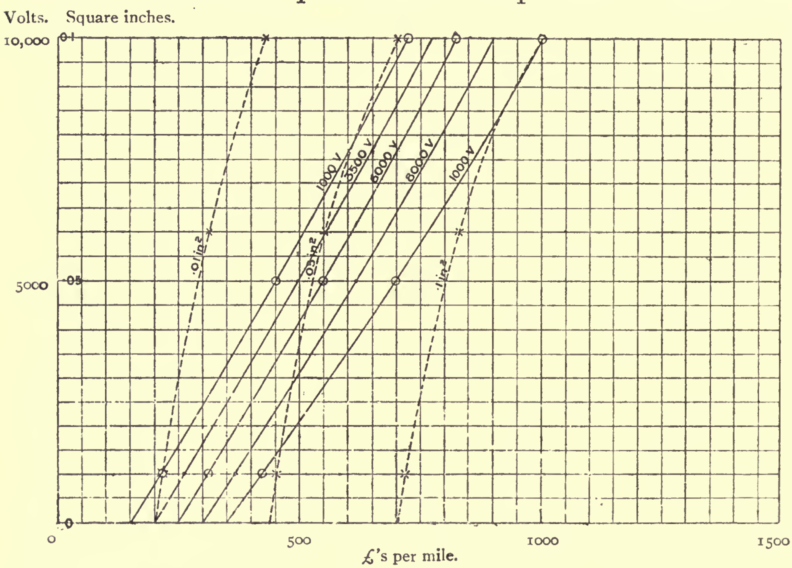

Fig. 21.

constant area curves, points can be read off for the price curves at constant volts of 3500 and 8000.

Now the area of each core of a three-core cable delivering KW. kilowatts at E volts between cores, with a loss of p per cent. of these kilowatts per mile transmitted, at 15° C. is—

$$Ap = \frac{KW}{E^2} \times \frac{4224}{p} \text{ins}^2.$$

To do the same as above, but at a density of Δ amperes per square inch instead of at a loss of p per cent., the area of each core would be—

$$A\Delta = \frac{KW}{E} \times \frac{588}{\Delta} \text{ins}^2.$$

The areas required for 10, 50, 100, 500 and 1000 kilowatts at a loss of 2 per cent. per mile, as calculated by the above expression, are as follows :—

KW.'s at	1,000	3,500	6,000	8,000	10,000 volts.
10	0·021	0·00172	0·00058	0·00033	0·00021 ins.²
50	0·105	0·0086	0·0029	0·00165	0·00105 ,,
100	0·21	0·0172	0·0058	0·0033	0·0021 ,,
500	1·05	0·086	0·029	0·0165	0·0105 ,,
1000	2·1	0·172	0·058	0·033	0·021 ,,

The prices of these read from the price curves are as follows :—

KW.'s at	1,000	3,500	6,000	8,000	10,000 volts.
10	280	210	255	—	— £.
50	750	250	275	315	360 ,,
100	—	305	285	320	370 ,,
500	—	700	430	415	430 ,,
1000	—	—	605	515	500 ,,

These are plotted on Fig. 22.

It is seen from this that each load has a cheapest voltage, and also how this "cheapest voltage" increases with the KW.'s to be transmitted.

If, instead of the loss, the density were kept constant, a similar set of figures would be obtained, but giving a slightly different "cheapest voltage."

Although, with the exception perhaps of telegraph wire, the material almost universally used for electric conductors is copper, there are other metals which have certain claims for consideration as possessing advantages in one way or another over copper.

In order to make a comparison, one must be sure of the basis of comparison selected. In general the problem is one of transmitting a certain quantity of electrical energy a certain distance with a given loss in the process; thus the comparison might be in the

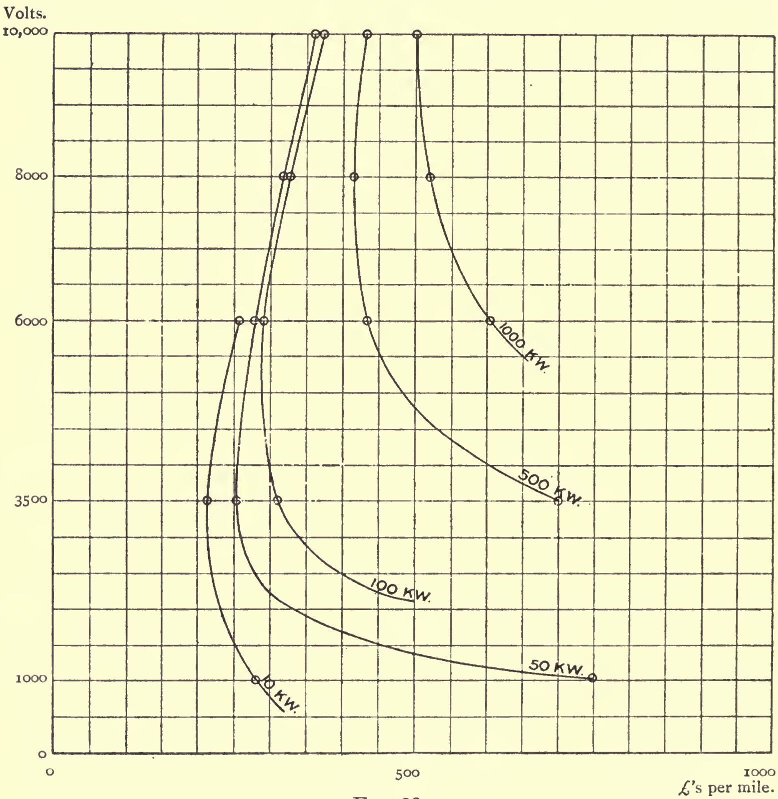

Fig. 22.

cost of a conductor one mile long having a resistance of one ohm. There are other considerations, of course, besides the one of cost. The diameter of the conductor is important as affected by wind and snow. The weight

of the conductor has a direct bearing on the cost of poles, and its strength must be considered in this connection, in relation to its weight.

For the solution of the problem as stated above, four of the properties of the material of the conductor must be known, namely, its specific resistance, its density, its tensile strength, and its cost per ton.

If ρ be the specific resistance in 10^{-6} ohms per cm. length per cm^2. area at 15° C.,
and δ be the density in grammes per cm^3.,
S be the tensile strength in tons per in^2.,
K be the cost in £'s per ton,

then the diameter of the conductor of one ohm per mile will be $0 \cdot 178\sqrt{\rho}$ inches.

The weight per mile will be $\frac{\rho \times \delta}{39 \cdot 3}$ tons, and the cost per mile $\frac{\rho \times \delta \times K}{39 \cdot 3}$ £'s.

The strength of the conductor considered in relation to its weight may be expressed as the number of miles of itself that the conductor would support vertically; this $= \frac{S}{\delta}$ very nearly indeed.

In the table on next page are given a few of the possible metals of which conductors might be made, with their four physical properties as above, from which are worked out the particulars of the one ohm per mile conductor.

It should be noted that the cost given is for the material of which the conductor is made, and does not

include the cost of making it into a wire or other suitable form; for instance, sodium would probably have to be contained in an iron tube.

Material.	Microhms per cm³. at 15° C. ρ	Grammes per cm³. δ	Tensile strength, tons per in². S	£'s per ton, London, Sept. 30, 1910. K	Conductor 1 mile long 1 ohm resistance at 15° C. Inches diameter.	Tons weight.	Length of itself it will support.	Cost. £
Aluminium	2·84	2·6	15·0	74	0·3	0·188	5·8	14
Antimony	37·0	6·7	0·4	28	1·08	6·3	0·06	176
Bismuth	136·0	9·8	3·8	896	2·08	34·0	0·39	30,500
Brass, Cu $\frac{2}{3}$ Zn $\frac{1}{3}$ ...	6·5	8·4	22·0	48	0·455	1·39	2·6	67
Bronze, Cu, Sn, P or Si	3·3	8·9	40·0	69	0·324	0·75	4·5	52
Cadmium	10·6	8·6	5·2	336	0·58	2·32	0·6	780
Copper	1·67	8·9	26·0	59	0·23	0·38	2·9	22·4
Gold	2·32	19·3	17·5	139,000	0·271	1·14	0·9	158,000
Wrought iron ...	10·5	7·8	40·0	6	0·57	2·09	5·1	12·5
Cast iron	100·0	7·2	9·0	3	1·78	18·3	1·25	55
Lead	21·0	11·4	1·4	13	0·82	6·1	0·12	79
Magnesium	4·6	1·7	12·0	672	0·382	0·2	7·0	134
Mercury	95·3	13·6	—	250	1·74	33·0	—	8,250
Nickel	13·4	8·9	39·0	171	0·65	3·04	4·4	520
Platinum	9·3	21·5	22·0	238,000	0·544	5·1	1·02	1,220,000
Silver	1·56	10·5	19·0	3,460	0·222	0·42	1·8	1,450
Sodium	5·2	0·97	0·01	90	0·406	0·128	0·01	11·5
Steel	15·0	7·8	60·0	5	0·69	3·0	7·7	15
Tantalum	16·5	16·5	27·0	13,000	0·725	6·9	1·6	90,000
Tin	13·8	7·3	2·0	157	0·66	2·56	0·27	40·5
Tungsten	10·7	19·1	11·0	560	0·58	5·2	0·58	2,900
Zinc	6·1	7·1	3·4	24	0·44	1·1	0·48	26·4

Below are given eight of the more interesting metals arranged in order of merit under the four different counts. For the sake of comparison, copper has been taken as a standard and called one, the others being compared with copper.

Size.		Weight.		Strength (in length of itself it will support).		Cost.	
Silver	0·97	Sodium	0·34	Steel	2·6	Sodium	0·52
Copper	1·0	Aluminium	0·5	Magnesium	2·4	Wrought iron	0·56
Aluminium	1·3	Magnesium	0·53	Aluminium	2·0	Aluminium	0·63
Bronze	1·4	Copper	1·0	Wrought iron	1·8	Steel	0·67
Magnesium	1·66	Silver	1·1	Bronze	1·5	Copper	1·0
Sodium	1·76	Bronze	2·0	Copper	1·0	Bronze	2·3
Wrought iron	2·47	Wrought iron	5·5	Silver	0·6	Magnesium	6·0
Steel	3·0	Steel	7·9	Sodium	0·003	Silver	65·0

All compared for a conductor of equal resistance per mile.

It will be noticed that the somewhat curious result is arrived at that sodium forms both the cheapest and the lightest conductor, whilst aluminium is better than copper in everything but size ; wrought iron and steel are cheap and strong, but very heavy and large. By far the most costly conductor of all is platinum, although it is for the purpose of an electrical conductor that the largest part of the world's output of platinum is used, namely, in the manufacture of electric lamps.

CHAPTER XII

CHOKING COILS

It sometimes happens that it is required to reduce the amount of current flowing in a circuit. In direct-current work this would have to be done by inserting a series resistance, with its consequent waste of energy ; a back electro-motive force would do the work better and more economically, but is difficult to arrange. In alternating-current work, however, a method exists of readily manufacturing this back E.M.F on the spot in the piece of apparatus known as a choking coil.

This consists of a magnetic circuit, either wholly of iron or partly of iron and partly of air, round which is wound the conductor carrying the main current. The current flowing round the iron magnetizes it, thus causing an alternating flux to flow, this in its turn creates an alternating E.M.F. in the conductors encircling it.

Such a number of turns is wound round the iron as will, multiplied by the maximum value of the current, give the ampere turns needed to send that flux round the circuit which will give the required back E.M.F.

It follows from the principles discussed in the first chapter of this book that this back E.M.F. is at right angles to the current.

Suppose that it is required to work a 50-volt 10-ampere arc lamp from a 100-volt circuit; the current of an arc being in phase with the voltage across it, the choking coil voltage is at right angles to this latter, the supply voltage being the resultant of the two. The choking coil will therefore be required to give a voltage equal to $\sqrt{100^2 - 50^2}$ or 86·5.

Assuming a 50 $\sim$ circuit, the product of the flux and the turns will equal $\dfrac{86{\cdot}5 \times \sqrt{2} \times 10^8}{2\pi \times 50} = 39 \times 10^6$.

Taking the relation established for a transformer that the flux should be of the order of 90 times the total ampere turns, the flux would be 187,000 lines and the turns 208.

To carry these lines at an induction of, say, 10,000 lines per cm^2. requires 2·9 ins^2., or say $2'' \times 1{\cdot}65''$, allowing for insulation between the plates.

Ten amperes at 1500 amperes per in^2. requires 0·0067 in^2., or 0·092″ diameter, which covered to 20 mils. equals 0·112″. Winding this to 7 layers and 15 convolutions per layer on each coil, gives a coil 0·8″ deep and 1·8″ long. The inside dimensions of the stamping will be $2'' \times 2''$ and the outside $6'' \times 6''$. The yoke piece would, of course, be separate, in order to slip the coils over the two limbs.

The mean path of the lines in the iron would be $14'' = 36$ cms. H for $B = 10{,}000$ is about 3, making $H \times l = 108$ for the iron. The total magnetizing force of the two coils carrying 10 R.M.S. amperes is

$\frac{10 \times \sqrt{2} + 208}{0{\cdot}8} = 3660$, which leaves 3552, which can be used up in the air space between the removable yoke and the two limbs. The induction in this air space is also 10,000, which means 0·055 cm., or from $1\frac{1}{2}$ to 2 millimetres a side, which can take the form of mica packing and is readily adjustable to obtain the exact back E.M.F. required.

The mean turn of the coil is about 11 inches, so that the resistance of the 208 turns is 0·23 ohm cold, and the copper loss warm with 10 amperes is 26 watts.

The weight of the iron is 13 lbs., which at 2 watts per pound also gives a loss of 26 watts, or 52 watts lost in all. The volt ampere input to the choking coil is $86{\cdot}5 \times 10 = 865$, from which the power factor is 0·06. The power factor of the whole circuit consisting of arc and choking coil would be 0·55, the total power being 500 watts for the arc and 52 for the coil, and the input being 1 K.V.A.

In the continuous current analogy a series resistance of 5 ohms and a loss of 500 watts, or nearly ten times as much, would have been necessary.

At currents less than 10 amperes the back E.M.F. of the choking coil will be sensibly proportional to the current, but at much higher currents the iron will saturate: to give double the back E.M.F. would require an induction of 20,000 lines per cm^2. H would then be 290, making $H \times l$ for the iron $= 10{,}400$, and 7100 for the air, total 17,500 C.G.S. units or 48 amperes.

CHAPTER XIII

ADDITIONAL EXAMPLE OF THE DESIGN OF AN ALTERNATOR

THE alternator designed in Chapter IV. fulfils the requirements of a constant pressure generator with a good inherent regulation, but there may be uses for an alternator when these small pressure drops are out of place. For instance, in the case of an alternator for use with a resistance type of electric furnace it is more important to keep the KW. input to the furnace as nearly constant as possible with wide variations of the resistance offered by the furnace. This means that as the current increases the voltage should decrease in nearly the same proportion.

This result can be approached by the use of a large stator reaction combined with a large stator leakage flux; and it so happens that both these tend to cheapen the manufacturing cost per KW.

To illustrate this, let us consider the design of a two-phase alternator for furnace work giving, say, 500 K.V.A. total, at 130 volts per phase, frequency of 25, speed 100 r.p.m., 30 poles.

The full-load current per phase will be 1920 amperes.

A stator reaction of something like 1500 ampere turns per inch diameter will be possible; putting this value into the expression in Chapter III. gives $D^2l = 86,000$, which for a length of about 10″ gives a diameter of about 100 inches. The corresponding peripheral speed for this is 2600 feet per minute, and the pitch of the poles is 10·5 inches. All these figures are quite satisfactory.

The conductors per pole per phase at 1500 total ampere turns per inch diameter and 100 inches diameter and 1920 amperes per phase are 2·6. Call this 3; putting each conductor in a tunnel would mean 6 tunnels per pole, or 180 total; the pitch of the teeth would be 1·74″.

The stator conductor for a density, say, of 2500 amperes per in^2. would be 0·77 in^2.; this, at any rate for the conductor embedded in the tunnel, would have to be stranded, as otherwise the "Field effect" would nearly double the RC^2 loss in that portion. The stranding will increase the bulk of the conductor from 15 to 20 per cent. for the same conductivity.

The length of the turn on the stator is about 57 ins., which would make the resistance of the 45 turns per phase 0·0022 ohm cold, the lost volts warm 5, the total volts per phase 135, and the stator flux $2{\cdot}7 \times 10^6$ lines per pole.

In the design of the whole magnetic circuit we must allow for the voltage increasing as the load on the alternator falls, in order to keep the output to the furnace as nearly constant as possible, thus the induction

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in the teeth should not exceed, say, 15,000 lines per cm^2. at full load.

In a two-phase machine the pole arc should not be much more than half the pole pitch, so as to allow of one phase being entirely out of the field at one time. To do this in this case allows the pole a width of 3 teeth and 4 slots, or say, 6″.

The net length of iron in the 10″ length, allowing for three $\frac{1}{2}$″ ventilation spaces and plates 0·015″ thick, with 1 mil. of varnish on each side, is 7·5″. The teeth are then 0·93″ wide, leaving 0·81″ for each tunnel.

The copper could be 1·3″ × 0·7″, insulation all round with 0·05″ of, say, silesia varnished and ironed on; the tunnels could then be 1·5″ deep.

The iron at the back of the slots for an induction of say 12,500 would be 2·25″ deep each side, making the outside diameter of the stator plate 107·5″.

The stator leakage flux, taking for tunnels 100 lines per ampere per inch, at a current of 1920 amperes, is $2{\cdot}7 \times 10^6$, or curiously enough exactly equal to the stator flux.

It is safer to allow for a power factor of 0·95, which, however, is mostly accounted for by the leads and not by the furnace itself. The air space flux at this angle by the vector diagram is $4{\cdot}4 \times 10^6$. The rotor leakage factor is probably about 1·2, so that the rotor flux is $5{\cdot}3 \times 10^6$, to accommodate which in cast steel at 16,000 lines per cm^2. requires 51 ins^2. Make the pole, say, 10″ × 5″ and assume a length of pole of 6″. The yoke

if cast steel should be rather more than half this area, say, $10'' \times 3''$. Take the radial clearance as $\frac{1}{4}''$.

We have now all the data for the calculation of the full load magnetization, which works out as follows :—

SYNTHESIS AT 130 VOLTS, 1920 AMPERES, 0·95 POWER FACTOR.

	Length cms.	Area cms².	Flux $\times 10^6$.	B lines cm².	H per cm.	$H \times l$ C.G.S.	Ampere turns per pole.
Stator core ...	28·0	21.7	2·7	12,500	6	168	
Teeth	7·6	182	2·7	14,800	11	84	
Air space ...	1·27	387	4·4	11.400	11,400	14,480	
Magnets ...	30·0	323	5·3	16,400	47	1,410	
Yoke	22·0	387	5·3	13,700	6·5	143	
						16,285	6,500

The demagnetizing ampere turns on the stator are

$$\frac{1920 \times 45 \times 2 \times \sqrt{2}}{2 \times 30} = 4100$$

These two combined on the vector diagram give the rotor ampere turns at the above full load as = 10,100.

The rotor magnet winding may very well take the form of copper strip on edge. Exciting from 100 volts and allowing 36 inches for the length of one turn, the area for 10,100 ampere turns is 0·084 in²., say $1\frac{1}{4}'' \times 0{\cdot}067''$. This would carry 126 amperes at 1500 amperes per in². The turns would be 80 per pole. Separating these with 5 mil. paper, the winding would occupy 5·85″ radially : the magnet pole should be $6\frac{1}{2}''$ long.

The resistance cold of the 30 poles in series is 0·69 ohm, the loss warm 12·6 KW. or 2·5 per cent. of 500 KW.

The next thing required is the open circuit magnetization curve. Using the areas and lengths of the

magnetic circuit from the full-load synthesis, and taking four points, this works out as follows :—

Line volts at 100 r.p.m.	100	150	175	200
Stator flux × 10^6 ...	2	3	3·5	4
B and H Stator ...	9,200 – 3	13,800 – 8·5	16,200 – 23	18,400 – 130
Teeth ...	11,000 – 4	16,500 – 28	19,200 – 200	22,000 – 650
Air	5,200	7,800	9,100	10,400
Magnets ...	7,400 – 2	11,200 – 5·5	13,000 – 9	14,800 – 18
Yoke ...	6,200 – 1	9,300 – 3	10,800 – 5	12,400 – 8
H × *l* Stator ...	84	238	644	3,640
Teeth ...	30	213	1,520	4,950
Air	6,600	9,900	11,550	13,200
Magnets ...	60	165	270	540
Yoke ...	22	66	110	176
C.G.S. per 2 poles ...	6,796	10,582	14,094	22,506
Ampere turns per pole	2,720	4,240	5,640	9,000

This curve is drawn on Fig. 23 ; from it is found that the full-load magnetization would give 204 volts on open circuit, or a rise of 57 per cent.

The short circuit current for 10,100 ampere turns on the rotor is 2500 amperes.

We have now three points on the load curve connecting volts and amperes at constant speed, power factor, and rotor excitation—namely, 204 volts 0 amperes, 130 volts 1920 amperes, and 0 volts 2500 amperes. Drawing through these points the best curve we can (Fig. 24), it would be as well to check two more points, say, 188 volts 1000 amperes and 70 volts 2300 amperes ; these

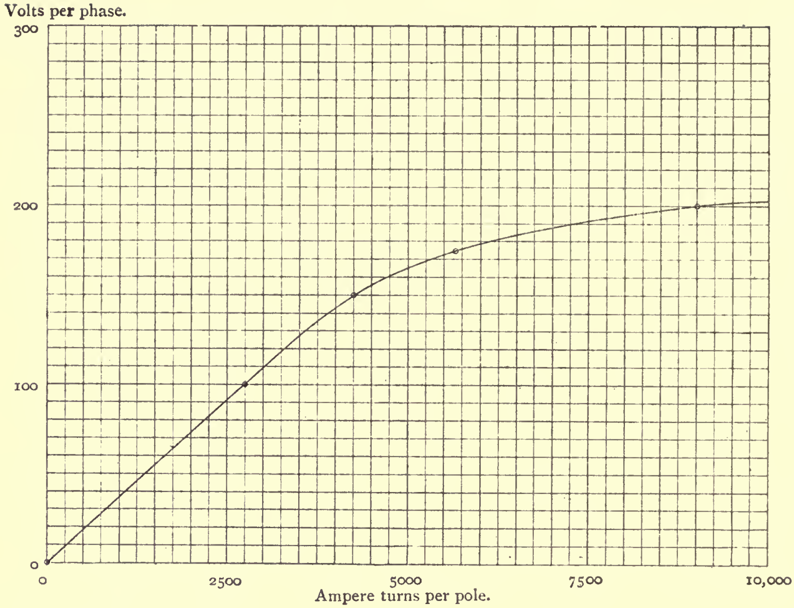
Volts per phase.
300
200
100
0
0
2500
5000
7500
10,000
Ampere turns per pole.

FIG. 23.


Volts per phase.
300
200
100
0
500 K.V.A.
0
1000
2000
3000
Amperes per phase.

FIG. 24.

are both found to require very nearly 10,100 ampere turns on the rotor.

On the same sheet is drawn the volt ampere curve for 500 K.V.A., which shows that for voltages between 100 and 200, the two curves do not widely differ.

The losses at full load are approximately as under—

Iron loss, 2580 lbs. at 1·75 watts per lb.	4·5 KW.
Stator copper = $2 \times 0{\cdot}0022 \times 1{\cdot}15 \times 1920^2$	18·6 ,,
Rotor copper = $0{\cdot}69 \times 1{\cdot}15 \times 126^2$	12·6 ,,
Total loss	35·7 ,,
Output = $500 \times 0{\cdot}95$	475·0 ,,
Input	510·7 ,,
Efficiency	93 per cent.

This rather low efficiency is not so much due to the peculiarities of the design as to the low speed for the output, necessitating a large amount of active material.

The weights and costs of active material are—

Stator iron	2,120 lbs.	at	30*s.* cwt.	£28·5
Stator copper	1,270	,,	1*s.* lb.	63·5
Rotor poles	3,000	,,	18*s.* cwt.	24·0
Rotor copper	2,320	,,	10*d.* lb.	97·0
Yoke ring	2,170	,,	18*s.* cwt.	17·5
	10,880 lbs.			£230·5

This could probably be sold at a profit for £900. If this is compared with the 250 KW. constant pressure alternator at 375 r.p.m. and 0·8 power factor, it is seen to be about one-third the cost on the basis of the K.V.A. at one r.p.m.

CHAPTER XIV

DESIGN OF A SMALLER TWO-PHASE SQUIRREL-CAGE INDUCTION MOTOR AND AUTO-STARTER

The design of the 50 H.P. wound-rotor motor described in Chapter VIII. may be supplemented by that of a smaller squirrel-cage motor ; this, of course, will suffer from the disadvantages of such a rotor winding : firstly, in starting, it will take a larger current from the mains, and even then it will not start up against such a large load in comparison with its rated H.P. ; and secondly, it will not be capable of speed regulation ; it will, however, have a slightly better power factor than the corresponding wound-rotor motor, and it will be considerably cheaper to build owing both to the simplicity of its rotor winding, and to the absence of slip rings and brush gear.

For the sake of example, let us take a 5-H.P. motor to work from a 50$\sim$, 2-phase, 3-wire circuit at 220 volts per phase. Speed light, 1500 r.p.m., *i.e.* 4 poles. The motor to stand 50 per cent. overload for a few minutes, and full load for 6 hours with a temperature rise of not more than 40° C.

The full load efficiency of such a motor should be about 85 per cent. and the power factor about 90 per

cent. The current per phase on this basis is about 11 amperes.

To obtain a power factor of 90, σ would $= \frac{0 \cdot 1}{0 \cdot 9}$ $= 0 \cdot 053$.

Take for a first approximation 4 slots per pole per phase in the stator, making 8 per pole and 32 total. The rotor slot number should be as dissimilar as possible from this, and also as high as practicable; try 45.

N in the σ formula would then be 9·6 and the first term 0·0325. δ, the radial clearance, could be as low, with good mechanical workmanship, as 0·5 mm. Making the length 12 cms. and taking advantage of the 30 per cent. decrease in the third term of the σ expression due to the squirrel-cage winding, the value of $\sigma = 0 \cdot 053$ would be satisfied with a pole pitch of anything over 9 cms.

Taking 300 ampere turns per cm. diameter, with 11 amperes per phase and 9 cms. pole pitch, the air space induction would work out to about 10,800; reducing this to 5000 would give pole pitch of 13·2 and a diameter at the air space of 17 cms. nearly.

On the foregoing assumptions the total turns for 17 cms. diameter are 464, which is 29 conductors in each of the 32 slots, making 232 turns per phase.

To carry 11 amperes at about 4 amperes per mm^2. requires 2·75 mm^2. No. 15 S.W.G. is 2·63 mm^2. area, which would make the density 4·2.

The average length of a turn on the stator would be

about 68 cms., the resistance per phase cold would therefore be 1 ohm, or about 13 volts lost, warm.

The total flux per pole in the stator will be $0{\cdot}42 \times 10^6$ lines.

$$\sigma \text{ will} = \frac{3}{(9{\cdot}6)^2} + \frac{10 \times 0{\cdot}05}{9{\cdot}6 \times 13{\cdot}4} + \frac{3{\cdot}5 \times 0{\cdot}05}{12}$$
$$= 0{\cdot}051$$

which makes the rotor flux $0{\cdot}4 \times 10^6$.

The 12 cms. length will have one ventilation space 1 cm. wide, and will have a net length of iron of 10·6 cms.

The width of each tooth for the induction never to exceed 17,000 lines per cm^2. will be 4·6 mm., which makes the slot 12 mm. wide. Insulating this with 0·5 mm. a side, leaving 0·5 mm. margin, and insulating the wire to 0·25 mm. on its diameter with, say, varnished silk, 5 wires will go in abreast. The overall depth of the slot will therefore be about 17 mm. with a 2 mm. opening.

The radial depth of iron at the back of the stator slots for, say, $B = 7000$ is 2·8 cms., making the outside diameter of the stator plate 26 cms.

The rotor copper per slot for a density of about 5 amperes per mm^2. is approximately

$$\frac{32 \times 29 \times 2{\cdot}63}{45} \times \frac{4{\cdot}2}{5} = 46 \text{ mm}^2.$$

This, in a round bar, has a diameter of 7·6 mm., which would go through a hole in the rotor plate of 8 mm. diameter, no insulation being necessary. The

minimum width of tooth would then be 3·4 mm., which is ample to carry the flux. The rotor plate could have a hole in its centre up to 11·5 cms. in diameter for the induction not to be over 10,000 lines per cm^2.

The end ring should have a cross-sectional area of a little less than half the rotor bars per pole, in this case about 15 mm. square.

The synthesis of the magnetic circuit works out as follows :—

	Length.	Area.	Flux.	B.	H.	$H \times l$.
Stator core × 2 ...	12·3	60	0·42	7,000	2	25
Stator teeth ...	3·4	46	0·42	14,400	10	34
Air	0·1	150	0·41	4,300	4300	430
Rotor teeth ...	1·6	42	0·4	15,000	12	19
Rotor core × 2 ...	7·2	40	0·4	10,000	3	22
				Total C.G.S. per 2 poles		530
				Ampere turns per pole		212

From this the magnetizing current per phase is

$$\frac{212 \times 4 \times 2}{\sqrt{2} \times 2 \times 232} = 2{\cdot}6 \text{ amperes.}$$

The static current is this divided by σ = 51 amperes. The Heyland diagram (Fig. 25) is drawn from these two currents.

The stator iron loss is approximately given by 55 lbs. of iron at 2 watts per pound = 110 watts ; add to this 30 watts for windage and friction and the fixed loss becomes 140 watts.

For the squirrel-cage rotor loss, the best we can do is to say that from actual data on similar motors the

full load slip will be about 5 per cent., which gives a rotor C^2R loss at full load of about 200 watts.

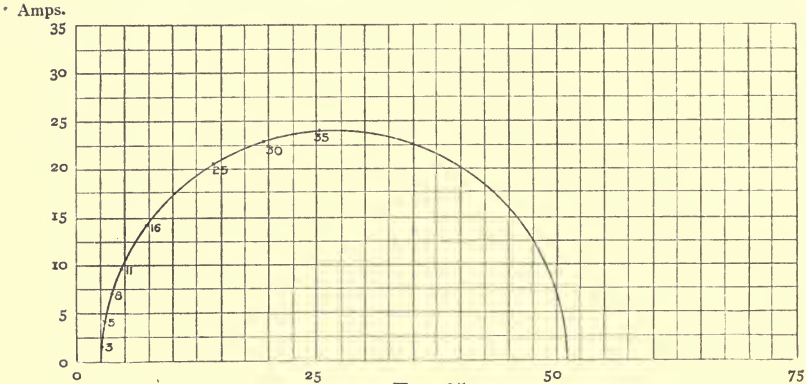

FIG. 25.

With the help of the Heyland diagram we can now work out the whole behaviour of the motor as under :—

Stator current.	In-phase component.	Power factor.	Stator C^2R.	Proportional rotor current.	Rotor C^2R.	Total losses.	Input.	Output.	B.H.P.	Slip per cent.	Efficiency per cent.
3	1·5	0·5	21	1·5	4	165	660	495	0·7	0·8	75·0
5	4·0	0·8	58	4·0	32	230	1760	1530	2·1	2·0	87·0
8	7·0	0·88	148	7·0	98	386	3080	2694	3·6	3·5	87·5
11	9·9	0·9	280	10·0	200	620	4360	3740	5·0	5·1	86·0
16	14·2	0·87	590	15·0	450	1180	6200	5020	6·7	8·2	81·0
25	20·5	0·82	1440	23·5	1100	2680	9000	6320	8·5	14·8	70·0
30	23·0	0·77	2070	28·5	1620	3830	10200	6370	8·5	20·0	63·0
35	24·0	0·69	2840	33·0	2170	5150	10600	5450	7·3	28·0	51·0

These are plotted on Fig. 26.

For the power factor running light the losses are $140 + 16$ for $C^2R = 156$; the volt-ampere input is $2 \times 220 \times 2{\cdot}6 = 1140$, which makes the power factor about 14 per cent.

WEIGHTS AND COSTS OF ACTIVE MATERIAL.

Stator plates	43 lbs.	at 30*s*. cwt.	£0·58
Rotor plates	18 ,,	at 30*s*. cwt.	0·24
Stator copper	16 ,,	at 1*s*. lb.	0·8
Rotor copper	10 ,,	at 9*d*. lb.	0·38
			£2·0

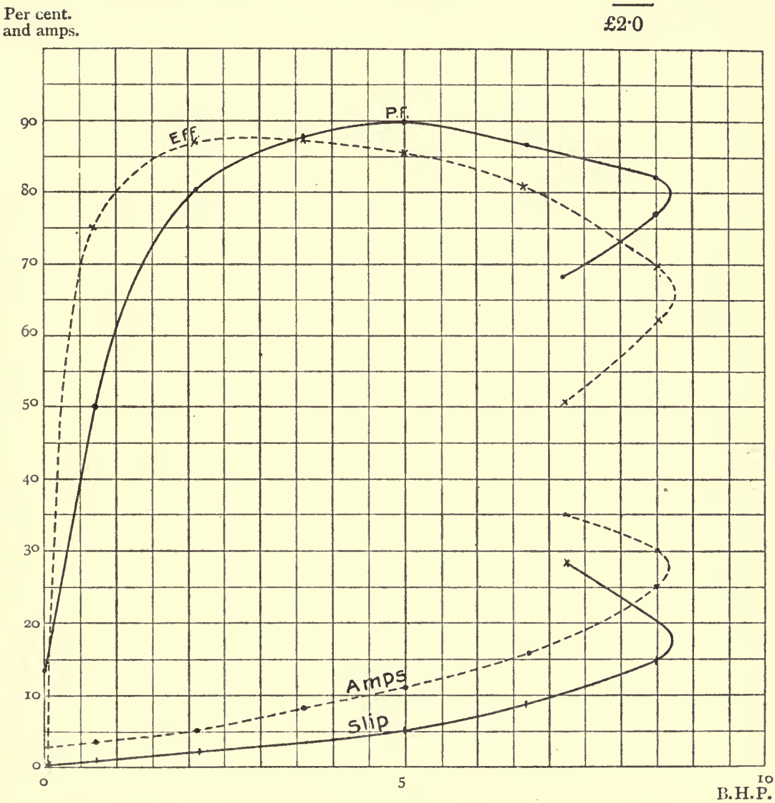

FIG. 26.

Auto-starter for the above motor.

To prevent the undue rush of current which would result from switching the stator of such a motor straight on to the mains an "auto-starter" is employed. This device performs two functions, firstly, it causes a reduced voltage to be applied to the motor when starting up,

which consequently reduces the current sent into the motor; and, secondly, by doing this by means of a transformer, the actual current demanded from the mains is less than the current sent into the motor by nearly the same proportion in which the voltage on the motor is reduced from that of the mains.

If a coil of wire is wound round an iron core and an alternating voltage applied at its ends, the voltage will be divided up proportionately to the turns, *i.e.* a point halfway along the coil will give half the line voltage from that point to either end of the coil; but not only this but the half number of turns will act in every way as the secondary windings of a transformer on the same core, and, neglecting the small loss in the core and winding, will deliver the same volt amperes as are supplied by the mains, giving a greater current as the voltage is reduced.

This is just what is wanted for the starting up of a squirrel-cage induction motor. A suitable switch will apply consecutively higher voltages to the motor as its speed increases, finally leaving the motor straight on to the mains with the auto-transformer coil switched off.

The two phases must, of course, be wound on separate iron cores, but can share a common yoke like the three-phase transformer, but unlike this, must have an iron circuit to take the resultant flux, which in the two-phase case is $\sqrt{2}$ times the flux of each phase, whilst in the three-phase case the resultant flux, of course, vanishes.

In the case under review the voltage per core is 220 and the frequency 50. If the motor is tapped on to the

middle of the winding, each half will contribute current equally, so that if we wind with a conductor which will carry the full-load current of the motor at, say, 5 amperes per mm^2., it will enable the motor to have two or three times its normal current whilst starting up with safety.

Eleven amperes at 5 amperes per mm^2. requires $2{\cdot}2\ mm^2$; 16's S.W.G. is $2{\cdot}1\ mm^2$. The wire will have to be well insulated, as the voltage per turn is high.

As the auto-transformer is only used for short times together, the induction in the iron core can be as high as about 17,000 lines per cm^2. A core 5 cms. $\times$ 4, built, of course, of laminated iron, will carry $0{\cdot}3 \times 10^6$ lines, which will require 330 turns for 220 volts.

16's S.W.G., insulated to 0·5 mm., is 2·13 mm. in diameter; 330 turns would make a coil 7·5 cms. long and 2 cms. deep. The iron cores would be 8 cms. long, the yoke 4 cms. high, and the unwound iron return in the centre 5·5 cms. wide, all being, of course, the 5 cms. deep.

APPENDIX

Equivalents of English and Metric Measures.

1 inch = 2·54 centimetres.
1 square inch = 6·45 square centimetres.
1 cubic inch = 16·39 cubic centimetres.

Densities of Metals.

Copper : 1 cubic inch weighs 0·32 pound.
Iron : 1 cubic inch weighs 0·28 pound.

Resistance of Copper.

1 inch of copper conductor of 1 square inch area has a resistance of $\frac{2}{3} \times 10^{-6}$ ohms at 60° Fahrenheit.

1 centimetre of 1 square centimetre area = $1{\cdot}7 \times 10^{-6}$ ohms at 15° C.

15 per cent. increase in resistance allows for a temperature rise of about 70° F. or 40° C.

Speeds of Synchronous Alternating Current Machines.

Poles.

Frequency.	2	4	6	8	10	12	14	16	18	20	22	24
25	1500	750	500	375	300	250	214	188	167	150	136	125
30	1800	900	600	450	360	300	257	225	200	180	164	150
40	2400	1200	800	600	480	400	343	300	267	240	218	200
50	3000	1500	1000	750	600	500	429	375	333	300	273	250
60	3600	1800	1200	900	720	600	514	450	400	360	327	300
100	6000	3000	2000	1500	1200	1000	857	750	667	600	545	500

Poles.

Frequency.	26	28	30	40	50	60	70	80	90	100	120	150
25	115	107	100	75	60	50	43	38	33	30	25	20
30	138	129	120	90	72	60	51	45	40	36	30	24
40	185	171	160	120	96	80	69	60	53	48	40	32
50	231	214	200	150	120	100	86	75	67	60	50	40
60	277	257	240	180	144	120	103	90	80	72	60	48
100	462	429	400	300	240	200	171	150	133	120	100	80

H.-B. Curve used in Examples of Design.

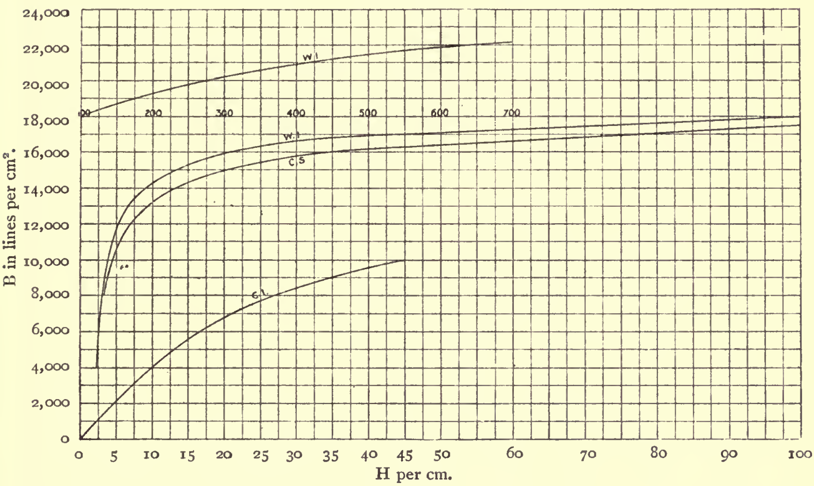

Fig. 27.

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